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RADC-TR-68-114, Volume I
Final Report

DATA COLLECTION FOR NONELECTRONIC RELIABILITY HANDBOOK (NEDCO I & NEDCO II)

William Yurkowsky
Hughes Aircraft Company

TECHNICAL REPORT NO. RADC-TR- 68-114
June 1968

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

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FOREWORD

This final report covers work performed by Hughes Aircraft Company, Ground Systems Group, Fullerton, California under RADC Contract AF 30(602)-4242, NEDCO I and NEDCO II from March 1966 to January 1968. The Project Managers were R. E. Schafer and W. Yurkowsky and Project Engineers were J. R. Collins, J. E. Davis, J. N. Holtz, L. C. Karaki, M. L. Luden, and J. S. Sheffield. The RADC Project Engineer was D. W. Fulton (EMERR). The Hughes Report Number is FR 68-16-84. The Project Number is 5519 and Task Number 551902.

This technical report has been reviewed and is approved.

Approved: DONALD W. FULTON
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ABSTRACT

This study addresses itself to the location, collection, classification, organization and analysis of nonelectronic part reliability information into a form from which it can be integrated into a Nonelectronic Reliability Handbook.

The study was logically divided into three steps: Data Search, Data Presentation, and Data Analysis. The Data Search was intensive and extensive. The major sources of nonelectronic part failure information were technical publications, symposia proceedings, Defense Documentation Center Reports, company reports, and information from other existing data banks. In all, 38,761 line entries of failure data on approximately 600 different nonelectronic part types were collected and stored on computer tape. The computer programs are designed to store and print out the data in the most convenient and useful form. All of the data collected are printed out in detail in the Appendix of this report.

The Data Analysis took several forms. Failure information on the same and similar part types was combined to yield overall failure rates for each of several environmental applications. Conversion factors were calculated to reflect the effect of varying severity of environments on part life. Failure rate versus stress relationships were sought but the data collected were not complete enough to yield useful relationships. Most of the failure information collected contained total part operating time and the number of observed failures. With this amount of information the only alternative was to perform the above mentioned analysis tasks as though the hazard rate was constant with time. Several reports were collected which gave good evidence that in truth many types of nonelectronic parts display failure times according to the Weibull distribution with increasing hazard rates with time. Therefore the failure rates and confidence limits computed based on the assumption of exponentially distributed failure times (where the true failure times are distributed according to some other failure function) should be used in the proper perspective and with care. While the use of the assumption of constant failure rate does yield a less precise estimate of the true hazard rate it is the only alternative as long as the failure data are recorded for these part types without the inclusion of individual part failure time.

Since it was established that the statistical methods applicable to the reliability of nonelectronic parts must differ from those used traditionally for electronic parts, prediction models applicable to nonelectronic parts were sought. Three models showing promise are investigated in the Data Analysis Section and are compared with field data collected during the study. In each case more verification is required but the models included appear to be useful contributions to the field of nonelectronic part reliability.

CONTENTS

EVALUATION

1. This study was addressed to the location, collection, organization and analysis of nonelectronic part failure data.

2. The study has resulted in 38,761 line entries of failure data on approximately 600 different nonelectronic part types. This represents the largest and most comprehensive collection of such data available to those engaged in design and reliability activities. It was necessary to assume a constant failure rate since for most of the data only the total part hours and number of failures were given. Where life-times were available, the distribution of times-to-failure almost invariably took the Weibull form with increasing failure rate. This is not a good situation since we have strong evidence that our assumption is wrong. The decision taken in this study has been to provide the upper 90 percent confidence limit in addition to the point estimate of the failure rate. The use of the former in predictions will tend to preclude overly optimistic reliability predictions. The quality of the data was adequate to allow the development of application "K" factors. Significant differences in the numerical value of the "K" factor are found to exist between part families within a common application and also between the subclassifications of a part family. The fallibility of a single "K" factor applicable to all part types is well illustrated. Attempts to relate failure rates to applied stress were not successful, not that there is no relationship but rather due to insufficient specific information within the collected data.

3. This collection will reasonably serve needs for nonelectronic part failure data so long as the user exercises care and recognizes the tenuous nature of the basic assumption of a constant failure rate. Future activities in data collection will be directed exclusively at the determination of hazard rates and stress/hazard rate relationships.

Donald W. Fulton

DONALD W. FULTON
Reliability Engineering Section
Reliability Branch

SECTION 1
INTRODUCTION

PAGE

1.0 Introduction

1.1 Objectives

The broad objective of this study was to locate, collect, organize and analyze reliability information on nonelectronic parts which can be used in the preparation of a Nonelectronic Reliability Handbook.

While the above statement represents the overall objective of the study, there were several specific objectives which more fully explain the nature of the effort which was undertaken.

The first of these was to establish the needs of potential users of such a bank of data in terms of part types, environmental applications and operating characteristics. A data needs survey was conducted and its results were used to direct the course of the data collection effort.

The next task was to locate, collect, organize and analyze nonelectronic part failure information from as wide a spectrum of parts and applications as was possible. Such a diverse body of information in order to be of optimum utility required a format for uniform presentation. Furthermore, computer storage was necessary to provide for ease of handling, convenient information retrieval, timely updating, editing, and analysis.

The analysis objectives were to gather a sufficient concentration of failure information on high population parts to result in the establishment of the relationships that exist between part life and operating stresses and between part life and environmental stresses. Another very important aspect of the analyses performed on the collected data was the establishment of the proper underlying distribution of failure times. Most of the reliability work performed to date on electronic parts has shown that these classes of parts display failure times which are distributed exponentially. On the other hand, there is a good deal of evidence in the literature to indicate that in the case of nonelectronic parts, failure times occur according to the Weibull distribution with an increasing hazard rate over time. When the exponential is the proper underlying distribution of failure times, the calculations attendant with reliability estimates are made with ease. With other failure distributions, the statistical methods of reliability are much more complex.

With ease of calculations as a possible goal, it was therefore the objective of another of the analysis tasks to evaluate the error introduced by making the exponential assumption (thus, reaping the benefits of simple calculations) when, in fact, the parts of interest displayed other underlying failure distributions such as Weibull, lognormal or gamma. These tasks can, in effect, be summarized as being directed toward the establishment of the proper statistical methods for use in the field of nonelectronic part reliability.

A final objective of the subject study program was to analyze the data which had been collected and present the predominant failure modes for a given part type in each of its several possible applications.

Objectives of the Study on Nonelectronic Part Data Collection

- Locate, collect, classify, organize and analyze reliability data on different nonelectronic parts from different environments.
- Develop a format for data organization and presentation.
- Computerize the data for ease of handling, retrieval, updating, editing, and analysis.
- Relate failure rate and operating stresses.
- Relate failure rate and environmental stresses.
- Relate failure mode and application.
- Investigate the proper statistical methods of nonelectronic part reliability.
- Evaluate promising useful prediction and demonstration models for nonelectronic parts.

1.0 Introduction
1.2 Summary of Results

The search for reliability information on nonelectronic parts was very complete and it yielded a large amount of failure information on many different part types used in many different applications.

The success of the data collection effort for reliability information on nonelectronic parts can be expressed in terms of the large number of line entries of data gathered. This amounts to 38,761 pieces of data representing nearly 600 different types of nonelectronic parts. The reliability information collected was generated in close to 30 different environmental applications and over 100 different failure reports were collected on each of approximately 30 different part types.

The data was not distributed uniformly over either generic part types or environmental application. For example, over 80% of the data collected was generated in airborne applications, approximately 5% was from ground installations, and less than 1% of the failure reports were from shipboard applications.

Another measure of the success of the data collection effort is the completeness of detail that was available. The solicitations for reliability information on nonelectronic parts requested a very complete description of part, application, environment, failure time, failure mode and date of generation of the data. Unfortunately, the data which were collected (which are a true reflection of the state of the art of nonelectronic part failure information) were far from complete in the detail required to make exhaustive analyses. Therefore, some of the analyses which were performed appear to have been made as though the failure times were exponentially distributed even in the face of contrary evidence. This was done only because the bulk of the failure data which is available for nonelectronic parts has been collected without regard to individual failure times. The failure reports record only the total number of part operating hours and the number of failures. Hence, it is not possible to make any analysis other than one based on the assumption of exponentially distributed failure times. It might be pointed out, however, that since failure times were not recorded it is not even possible to verify whether or not the exponential distribution holds. In the light of this fact, the user of the reliability information collected and analyzed in this study should regard it with proper caution. Although it is not complete enough in detail, it reflects the quality of the data that is available at this point in time.

This introduction presents a general description of the objectives of this study program and summarizes its findings and conclusions. The remainder of the report discusses in detail each integral task performed during the course of the total effort. Section 2 outlines the philosophy and general approach which guided the course of the data collection as well as giving the specific sources from which failure information on nonelectronic parts was solicited. Section 3 details the classification, organization, and data formats used for

presentation of the part failure information in useful form. It discusses also the computer programs developed to manipulate the thousands of pieces of information on a wide variety of part types and distinct applications. Section 4 deals with each of the different types of analyses performed on the data collected and presents these results in their most useful form. Section 5 summarizes the Conclusions of the study effort while Section 6 lists the Recommendations based on the findings. The Appendix contains the detailed raw data developed in the analysis task as well as the individual line entries of failure information collected during the study.

SECTION 2
DATA SEARCH

2.0 Data Search

2.1 Preliminary Investigations

The scope of the search for nonelectronic part reliability data was centered on those parts defined as being not purely electronic in operational characteristics.

Many of the failure rate handbooks now in existence contain part failure data on electronic parts and on a few nonelectronic parts. The scope of the present data collection effort was directed exclusively toward the acquisition of failure information on as many different nonelectronic parts as possible.

In order to obtain the proper perspective on the scope of the study, it is imperative that the term nonelectronic part be defined. A nonelectronic part as used in this study is defined by exclusion. It is any part that is not purely electronic in nature. Examples of electronic parts are solid state devices, tubes, inductive and capacitive devices, and integrated circuit devices. All others are considered to be nonelectronic parts and hence failure information was sought on them for inclusion into this data bank.

The collection of such a large and varied amount of reliability information required a specific plan in order to be accomplished in an economical manner. Therefore, the first step was the development of a Data Needs Questionnaire to direct the course of the search.

The questionnaire dealt with such categories as the types of environments a potential user of this data was most concerned with, and the types of failure rate information that would be most useful such as derating curves, k factors, distributions of failure times, and other related information. An integral part of the questionnaire is shown on the facing page. This matrix was used to establish the detail of operational characteristics that would be sought during the data collection effort.

Because of the time limitations, the Data Needs Questionnaires were distributed on a limited basis to selected individuals within Hughes Aircraft Company and to several individuals in various Government agencies. Based on the results of the survey, the data collection effort was initiated on a broad scale within the scope of the definition of nonelectronic parts.

When the requests for failure information were sent out a great amount of detail was requested of contributors. It was hoped that if the data received were complete that a maximum amount of analyses could be performed on them. Included in the requests were a complete nomenclature describing the parts by size, type, model, application, part number and manufacturer. Also, a complete description of the environmental and operational conditions experienced by the parts was requested. Individual part failure times, failure modes and dates covered by the failure reports were requested. The data that were collected had all degrees of completeness of detail. One of the limiting factors in the utility of some of the data was the lack of detail accompanying the failure report. It would appear that for nonelectronic part data collection programs more detail is required than people are used to retaining.

ON WHICH COMBINATIONS OF COMPONENTS AND APPLICATION STRESSES DO YOU NEED ADDITIONAL AND/OR REVISED NONELECTRONIC RELIABILITY DATA?

PLEASE DOUBLE CHECK (//) THOSE OF PRIMARY INTEREST AND SINGLE CHECK (/) THOSE OF SECONDARY INTEREST.

COMPONENTS AND APPLICATION STRESSES LISTED ARE TYPICAL EXAMPLES. PLEASE ADD ANY COMPONENTS AND/OR APPLICATION STRESSES WHICH ARE OF PRIMARY INTEREST TO YOU.

TYPICAL APPLICATION STRESSES \ TYPICAL COMPONENTS	RELAYS	SWITCHES	SERVO MOTORS	GYROS	SYNCHROS	POTENTIOMETERS	CONNECTORS	BEARINGS	BELTS	VALVES	CLUTCHES	SPRINGS	WAVE GUIDE ROTARY JOINTS	GEARS	GASKETS AND SEALS	OTHER:	
VOLTAGE																	
CURRENT																	
POWER																	
ACTUATION RATE																	
TORQUE																	
LUBRICATION																	
MECHANICAL LOAD																	
PRESSURE																	
OPERATING SPEED																	
THERMAL																	
AXIAL/RADIAL IMPACT LOAD																	
TENSION																	
SLIPPAGE																	
INSERTION RATE																	
VIBRATION																	
OTHER:																	

Typical Page From Data Needs Questionnaire

2.0 Data Search
2.2 Areas of Search

A complete and comprehensive search was undertaken to locate and collect current reliability data on nonelectronic parts from every potentially useful source.

Since the definition of nonelectronic parts dictates a wide scope of search for reliability information on a great variety of part types, it was important to develop a systematic approach for the performance of this task.

The data collection effort therefore was conducted in three major areas. The first was a search of the literature. Six periodical indexes were consulted to develop a beginning list of source documents. One hundred eleven different technical periodicals were searched from the most current issues back to 1957. This date was established as a cutoff time for the inclusion of failure information from all sources in order that obsolete data not be included which would bias the current state of the art. Other important sources investigated in the literature search were the proceedings of technical conferences and symposia. Publications of proceedings from the past ten years on over 75 different types of symposia were carefully searched for pertinent information. Additional failure information was obtained by studying a great many Government technical publications from those in the Defense Documentation Center.

A major part of the data collection effort centered on information in existing data banks. All the principal data centers were solicited for their information on nonelectronic parts. The most notable contributor was FARADA. Approximately 22,000 line entries of information on nonelectronic parts were from that source. Information was received from several other existing data banks but in the majority of cases these reports were also included in FARADA and hence the data was not duplicated.

Personal contacts with individuals in Government and industry also constituted a major effort in the study. Over 200 letters were sent soliciting detailed failure information on nonelectronic parts. The mailing list included persons with reliability responsibility in major Government agencies and in companies thought to be large users and/or large producers of nonelectronic parts. The letters were in many cases followed up with phone calls. The response from this solicitation resulted in the receipt of useful information from sixteen sources.

Many valuable additions to the data base were made through a comprehensive search of internal Hughes field and laboratory test reports.

In December 1966 a preliminary report was published which tabulated the information collected up to that point in the program. The report has the designation RADC TR 66-828 "RADC Unanalyzed Nonelectronic Part Failure Rate Data Interim Report NEDCO I" and it contains 17,702 line entries of raw failure information. During the ensuing months, additional failure data were collected

and an improved data format was developed. The detailed results of the total data collection effort appear in Appendixes 7.10, 7.11 and 7.12 of this report.

- Proceedings of Conferences, Symposia, and Transactions
- Technical Periodicals
- Government Technical Publications
- Personal Contacts in Industry and Government
- Hughes Company Reports
- Existing Data Banks

Sources Investigated in NEDCO Data Search

SECTION 3
DATA PRESENTATION

PAGE

3.0 Data Presentation
3.1 Failure Rate Data

The most important considerations in the design of a presentation format were centered on allowing the user of this nonelectronic part reliability data bank access to accurate part identification and complete failure rate estimates.

The reliability information which was collected during the study was from hundreds of different sources and part types. To be of optimum utility, it had to be organized into a standard and convenient format for the benefit of the user.

The major concern of a user trying to locate reliability data applicable to his own problem is to properly identify the part of interest. It can be seen in the sample format on the facing page that a great portion of it is devoted to part classification and identification. The first five digits of the IDEP II Code numbering system were used to identify parts by generic type and by major sub-types. In the sample page, "Valves" are assigned the number 525, while "Hydraulic Valves" are designated by 525.60. The IDEP numbering system was used because it is apparent that much careful planning went into its conception and because it is widely used by many existing data banks for ease of information exchange.

Additional part descriptive information which was collected but which did not lend itself to classification by the part family code list was divided into two fields on the computer printout. That which described the part itself was listed in the PART DESCRIPTION field while that clarifying a subassembly or larger unit level from which the part was extracted was listed under FUNCTIONAL APPLICATION. Since no other space was available the FUNCTIONAL APPLICATION field was used to note certain operating conditions such as cycling rate, contact current or data from storage environments.

The other major positions in the computer printouts relate to the failure rate estimate. The failure rate is computed in failures per million hours, unless otherwise designated. An asterisk in the FAILURE RATE field indicates that no failures were observed. Additional backup for the failure rate is provided by the listing of PART POPULATION, PART HOURS and UPPER 90% CONFIDENCE LIMIT. The 90% level was selected since it seems to be the one most frequently used in reliability analyses.

The upper one sided confidence limits were presented since this decision rule gives conservative failure rate estimates when the Type I error is made in testing a hypothesis.

The failure rate estimates presented and the confidence limits calculated are based on the assumption of a constant failure rate. This was done even in the face of contradictory evidence for some nonelectronic parts because it reflects the type of failure data in existence today. A complete list of Failure Rate Data appears in Appendix 7.10.

ROME AIR DEVELOPMENT CENTER, GRIFFISS AFB, N.Y. — NONELECTRONIC PART FAILURE RATE DATA — JANUARY 1968

SECTION I FAILURE RATE DATA

PART CLASS 525 VALVES

PART DESCRIPTION	FUNCTIONAL APPLICATION	ENVIRONMENT	FAILURE RATE	UPPER 90 CONF LIMIT	PART POPULATION	PART HOURS	YR OF RPT	DATA SRCE	CROSS INDEX REF NO
.60 HYDRAULIC									
SELECTOR	BRAKE.EMERGENCY	AIR	330.266	425.571	50	.08478	63	1198	66844000
SELECTOR	BRAKE.LANDING-GEAR	AIR	342.061	438.765	50	.08478	63	1198	66846000
SELECTOR	BRAKE.LANDING-GEAR	AIR	373.333	481.066	50	.075	63	1114	66848000
SELECTOR	LANDING-GEAR-DOOR	AIR	1531.39	2359.36	43	.00653	66	1240	66850000A
SELECTOR.SHIFT		AIR	343.866	376.583	424	.538	64	1266	66852000A
SELECTOR.SOLENOID	UTILITY-SYSTEM	AIR	76.3825	97.5534		.39276	66	1241	66854000
SELECTOR.4-WAY	SPEEDBRAKE	AIR	350.59	447.763		.08557	53	1123	66856000A
SEQUENCE.PRESSURE		AIR	*	23.1719		.09937	63	1123	66858000A
SERVO	SURFACE-TO-AIR-MISSILE(STORAGE)	GRD	*	6.5172	12	.33288	64	1191	66860000
SERVO	WING-FLAP-SYSTEM	AIR	*	55.9834	78	.04113	66	1250	66862000
SERVO	(STORAGE)	GRD	*	35.0671	3	.0657	64	1191	65864000
SERVO	(STORAGE)	MSL	.250896	.421896	7518	27.9	55	1254	66866000
SERVO	HORIZONTAL-STABILIZER	AIR	35.0048	56.8592	946	.22854	65	1228	66868000
SERVO	RUDDER-SYSTEM	AIR	56.8828	82.9524	946	.22854	65	1228	66870000
SERVO	HORIZONTAL-STABILIZER	AIR	60.6284	71.8765	1194	1.0357	67	1272	66872000
SERVO	AILERON-SYSTEM	AIR	61.2584	88.0721	946	.22854	65	1228	66874000
SERVO	AILERON-SYSTEM	AIR	62.7424	94.6734	812	.17532	64	1179	66876000
SERVO	AILERON-SYSTEM	AIR	62.7594	73.9615	1194	1.0357	67	1272	66878000
SERVO	HORIZONTAL-STABILIZER	AIR	68.4462	101.423	812	.17532	64	1179	66880000
SERVO	POWER-CONTROL.RUDDER	AIR	87.9286	147.857		.07961	63	1123	66882000
SERVO	WING-FLAP-SYSTEM	AIR	121.359	270.258	48	.02472	65	1227	66884000
SERVO	RUDDER-SYSTEM	AIR	125.518	140.837	1194	1.0357	67	1272	66886000
SERVO	RUDDER-SYSTEM	AIR	154.004	199.402	812	.17532	64	1179	66888000
SERVO	THRUST-VECTOR-ACTUATOR(PITCH). CONTROL-SYSTEM	GRD	1739.13	3475.45		.0023	62	1135	66890000
SERVO	INBOARD-AILERON-GR-DRIVE	GRD	1739.13	3475.43		.0023	62	1135	66892000
SERVO	INBOARD-RUDDER-GEAR-DRIVE	GRD	1739.13	3475.45		.0023	62	1135	66894000
SERVO	THRUST-VECTOR-ACTUATOR(YAW). CONTROL-SYSTEM	GRD	2608.69	5579.17		.0023	62	1135	66896000
SERVO	ELEVATOR-ACTUATOR.CONTROL	GRD	4347.82	6698.54		.0023	62	1135	66898000
SERVO	BULKHEAD-GEARBOX.CONT-SYSTEM	GRD	10434.7	13731.9		.0023	62	1135	66900000
SERVO.BALANCE	POS-NOSE-WHEEL	AIR	310.486	359.881		.29786	65	1241	66902000
SERVO.FOLLOWUP	STEERING.NOSEWHEEL	AIR	15.4472	25.0916	597	.51799	67	1272	66904000
SERVO.3-WAY.1-STAGE	(STORAGE)	GRD	*	1.07653	117	2.1389	64	1191	66906000
SERVO-FOLLOWUP	STEERING.NOSEWHEEL	AIR	8.7512	34.0395	473	.11427	65	1228	66908000
SERVO-FOLLOWUP	STEERING.NOSEWHEEL	AIR	11.4077	44.3725	406	.08766	64	1179	66910000
SERVO-SELECT	WING-SPOILER-SYSTEM	AIR	40.453	157.35	48	.02472	65	1227	66912000
SERVO-SELECT	WING-SPOILER-SYSTEM	AIR	72.9394	162.431	76	.04113	66	1250	66914000A
SHUT-OFF-GATE	HYDRAULIC-POWER.707-1312	AIR	70P				66	2364	66916000
SHUT-OFF-GATE	HYDRAULIC-POWER.707-1312	AIR	70P				66	2362	66918000
SHUT-OFF-GATE	HYDRAULIC-POWER.880	AIR	80P				66	2363	66920000
SHUT-OFF-GATE	HYDRAULIC-POWER.880	AIR	80P				65	2365	66922000
SHUT-OFF-GATE	HYDRAULIC-POWER.707.331	AIR	140P				66	2361	66924000
SHUT-OFF-GATE	HYDRAULIC-POWER.707-331	AIR	150P				66	2362	66926000
SHUT-OFF-GATE	HYDRAULIC-POWER.707-331	AIR	160P				66	2364	66928000

Typical Page Showing Section I Format

3.0 Data Presentation

3.2 Environmental and Application Stress Format

The detailed information collected on the environmental and application stresses of nonelectronic parts is organized into a separate computer printout which is keyed to the Failure Rate Format by means of a cross index reference number.

It would have been desirable to arrange the data format in such a manner that it was possible to present every detailed piece of information from a given failure report as a single line entry. However, this was physically impossible due to the limitations of the computer printout equipment. Therefore, those details relating to a part's environmental and operational envelopes have been arranged as a separate body of information as shown in the sample on the facing page.

The part nomenclature and code number is not repeated in this section; however, a user of the data can relate the line entry in this section (Appendix Subsection 7.11) with the one in the Failure Rate Section (Appendix Subsection 7.10) by means of a cross index reference number. In the sample page presented here, this identifying number consists of eight digits and appears in the left hand column. The line entry in the Failure Rate Section for the part nomenclature and failure rate information corresponding to a given line entry of this section displays the same cross index reference number in the right hand column of the page.

A user of this data bank would very likely enter the computer listings with a given part type in mind. He would look up the part type in the Failure Rate Section and then proceed to this Section via the cross index reference number to discover information on operating and environmental stresses.

A complete listing of all of the operational and environmental data gathered is presented in Appendix Subsection 7.11. As can be seen by the sample on the facing page the major categories of operational information collected were related to a part's operational voltage, current, power, frequency or pressure. The major environmental conditions for which data were recorded were temperature, vibration, shock, pressure, and relative humidity. For relative humidity both a typical or nominal value and a range experienced by the part during normal operation is given where it is available. An example of this is shown on the facing page for cross index reference number 08576000 where the typical relative humidity was 30% and the range was from 0-50%.

The cross index reference numbers have been spaced with a gap of 1999 numbers between line entries so that future additions of data may be easily incorporated into the existing bank of information and still be entered alphabetically within the current body of data. If the gaps are eventually filled, the entire set of line entries may be resequenced and assigned new numbers, again with gaps for additional line entries subject to the limitations of the eight digits.

ROME AIR DEVELOPMENT CENTER, GRIFFISS AFB, N.Y.	NONELECTRONIC PART FAILURE RATE DATA	JANUARY 1968
SECTION II STRESS LEVEL DATA/PART NO		

CROSS INDEX REF NO	MIL STD PART NO/ FEDERAL STOCK NO	-PERCENT OF RATED- VOLTAGE	CURRENT	POWER	FREQUENCY	PRESSURE	-TEMPERATURE- DEGREES C TYP	HIGH	LOW	VIBRATION MECHANICAL SINUSOIDAL FREQ CPS	INT RMS G	RDM INT GXG CPS	ACOUSTICAL DB	SHOCK MAX INT G	DUR MIL SEC	BLOWS PER HR	PRESSURE TYP (PSIA)	RANGE (PSIA)	RELATIVE HUMIDITY PERCENT TYP	RANGE
08360000																				
08362000																				
08366000																				
08374000																				
08384000							21	27	16											
08390000																				
08396000		50	8																	
08442000																				
08444000	5935-259-4598																			
08454000	5935-504-4028																			
08478000																				
08538000								55	-54	25	.7									
08540000								55	-54	25	.7									
08542000								55	-54	25	.7									
08572000							25	30	20	30	.65									
08574000								71	-54	20-30	.2-.25									
08576000			8				25			30	1			0			15		30	0-50
08588000							25													
08590000							25													
08598000							52													
08608000							25													
08612000							25													
08614000								55	-54	25	.7									
08616000								55	-54	25	.7									
08618000								55	-54	25	.7									
08620000								55	-54	25	.7									
08622000																				
08634000		50	20				25	27	23								VAC			-1
08636000		50	10																	
08638000							25	30	20	30	.65									
08640000								55	-54	25	.23									
08642000								71	-54	20-30	.2-.25									
08644000			12				25			30	1			0			15		30	0-50
08672000																				
08686000	5821-991-8100																			
08690000																				
08692000																				
08738000	6340-073-7200																			
08774000	MS25276-1																			
08778000																				
08788000																				
08804000																				
08814000																				
08846000																				
08856000	6625-584-1924																			
08864000																				

Typical Page Showing Section II Format

The information gathered on the failure modes of nonelectronic parts is presented by part class in a separate format to allow the user to identify typical types and frequencies of failure modes to be expected.

The failure mode information is presented in a separate section so that emphasis may be laid upon recognizing predominant failure modes for each part type. The computer program used in generating this section of data is separate and distinct from the computer program responsible for the failure rate data and the stress and part number information.

On each page is noted the part class to which the line entries on that page belong. It is followed by a numbered list of possible failure modes applicable to that part type. On the sample page opposite, the part class cylinders is shown followed by twelve different descriptions of failure modes by which cylinders may fail, each description accompanied by a number in parentheses. The numbers of the failure mode descriptions are reproduced horizontally across the page just below the list of mode descriptions to serve as an index to the appropriate failure modes on that page.

The cross index reference number in Section III provides the means of locating part identification and description information and failure rate data in Section I (Subsection 7.10); line entries of data which have cross index reference numbers may be linked to that additional data in Section I. A missing cross index reference number indicates that no additional data is known, so no reference to Section I is made for that line entry.

Both the number of failures observed and the percent of those failures attributable to each failure mode is given for every line entry. For example, on the sample page opposite the line entry with cross index reference number 12090000 shows 207 failures, 59% of which were failures by mode (01), leaking; 8% by mode (03), out of tolerance; 14% by mode (05), broken or cracked; and 19% by mode (12), unknown.

ROME AIR DEVELOPMENT CENTER, GRIFFISS AFB, N.Y. NONELECTRONIC PART FAILURE RATE DATA JANUARY 1968
SECTION III FAILURE MODE DISTRIBUTIONS

PART CLASS CYLINDERS

FAILURE MODES (* DENOTES PREDOMINANT FAILURE MODE)
(1) LEAKING
(2) MECHANICAL DAMAGE
(3) OUT OF TOLERANCE
(4) BROKEN
(5) BROKEN OR CRACKED
(6) CRACKED
(7) INCORRECT OUTPUT PRESSURE
(8) STRUCTURAL FAILURE
(9) MECHANICAL
(10) ELECTRICAL
(11) WEAR OR AGING EFFECT
(12) UNKNOWN

CROSS INDEX REF NO.	NO.OF FAILURES	(01)	(02)	(03)	(04)	(05)	(06)	(07)	(08)	(09)	(10)	(11)	(12)
		FAILURE MODES BY PERCENT OF TOTAL FAILURES											
11952000	103	99	-	-	-	-	-	-	-	-	-	-	1
	11	64	-	-	-	-	-	9	9	-	-	-	19
12048000	2	50	-	-	-	-	-	-	-	-	-	-	50
	359	-	48	-	-	9	-	-	-	-	-	-	37
	24	-	9	-	-	-	-	-	-	-	-	32	50
	100	-	11	-	-	-	-	-	-	-	-	34	46
12118000	5	40	20	-	-	-	-	-	-	-	-	-	40
11946000	21	90	-	-	-	-	-	-	-	-	-	-	10
12020000	16	7	25	-	-	-	-	-	-	-	-	-	37
	72	-	30	-	24	-	-	-	-	-	-	11	35
	275	59	-	8	-	14	-	-	-	-	-	-	19
	395	53	-	9	-	-	13	-	-	-	-	-	25
	6	33	-	33	-	-	-	-	-	-	-	-	34
12090000	207	59	-	8	-	14	-	-	-	-	-	-	19
	88	59	-	-	21	-	-	-	-	-	-	9	11
12094000	352	-	-	-	39	-	-	-	-	-	-	14	47
	169	12	-	-	-	18	-	-	-	-	-	22	48
	119	27	-	6	-	-	-	-	-	-	-	49	18
	404	37	-	24	-	-	-	-	-	-	-	-	39
	364	-	-	18	-	-	-	-	-	-	-	33	49
	139	65	-	-	-	-	-	-	-	-	-	16	19
	184	70	-	-	-	-	-	-	-	-	-	16	14
	157	50	-	17	-	-	33	-	-	-	-	-	-
12070000	73	-	73	-	-	-	-	-	-	-	-	9	14
	14	36	-	-	50	-	-	-	-	-	-	-	14
	10	80	-	-	-	-	-	-	-	-	-	20	-
	510	-	-	-	-	-	-	-	-	-	-	70	30
12236000	12	25	-	-	-	-	-	-	8	42	25	-	-
12050000	3	100	-	-	-	-	-	-	-	-	-	-	-

Typical Page Showing Section III Format

SECTION 4
DATA ANALYSIS

4.0 Data Analysis

4.1 Failure Distribution Consensus

In the failure reports compiled on nonelectronic parts, evidence was sought which indicated that the report writer had analyzed part failure times to establish the proper underlying distribution.

The reliability data collection practices in current use appear to be geared to the implication that failure times for all parts, whether electronic or nonelectronic, are distributed exponentially. This statement appears to be true since generally the failure reports available only recorded total part operating time and number of observed failures. The only conclusion that can be made from this practice is that the person preparing the report did so by assuming that the parts on test exhibited a hazard rate that is constant with time. (Of course, if failure times were not recorded and analyzed, even the theory of a constant hazard rate with time could not be verified.)

This portion of the study was therefore directed toward searching for failure reports containing actual part failure times or at least where the author of the report indicated that he had analyzed the failure data collected for the proper underlying distribution of failure times.

A total of 39 failure reports were gathered on 10 different nonelectronic parts where this type of information was available. The table on the facing page summarizes these findings. The information is arranged in the form of a consensus. When different articles claimed different failure distributions for the same part type the number claiming each are listed. The "Consensus" column contains the ranges of the parameters found in the reports which were collected.

A review of the results indicates that there is strong evidence that many types of nonelectronic parts exhibit failure times distributed according to the Weibull distribution with the shape parameter greater than one. This is an indication of a hazard rate that increases over time. Bearings, relays, seals and switches clearly display these characteristics. Pumps and valve failure times are Weibull with shape parameter close to one which is for all practical purposes a constant hazard rate. For gears, two failure reports indicated exponential failure distributions while one was Weibull. Gyros and motors were featured by a consensus of a mixed Weibull distribution.

The conclusion to be reached from this phase of the study is that there is strong evidence that the exponential distribution does not hold for most nonelectronic parts. Therefore, to be absolutely correct the statistical methods used in the reliability analyses performed on electronic parts probably should not be applied to nonelectronic parts not exhibiting constant hazard rates. The following three topics investigate the effect of the exponential assumption when the correct underlying failure distributions are the Weibull, lognormal, and gamma.

The details of the information used to prepare the table on the facing page are given in Appendix Subsection 7.4.

Part Type	Total Number of Opinions Collected	Number of Exponential Opinions	Number of Weibull Opinions	Number of Mixed Weibull Opinions	Consensus
Bearings	12	0	12	0	Weibull $.5 < \beta < 4.0$
Gears	3	2	1	0	Exponential
Gyros	2	0	0	2	Mixed Weibull $\beta_1 = .6$ $1.7 < \beta_2 < 2.4$
Motors	4	1	1	2	Mixed Weibull $\beta_1 = .6$ $1.8 < \beta_2 < 2.25$
Pumps	1	0	1	0	Weibull $\beta = .99$
Relays	9	1	8	0	Weibull $.5 < \beta < 4.0$ $4x10^2 < \alpha < 8x10^{22}$
Seals	2	0	2	0	Weibull $.8 < \beta < 18.0$
Springs	1	0	1	0	Weibull $\beta = 1.47$
Switches	4	0	4	0	Weibull $.4 < \beta < 8.0$ $\alpha < 10^{43}$
Valves	1	0	1	0	Weibull $.8 < \beta < 1.0$

Consensus of Distribution of Failure Times for Certain Nonelectronic Parts

4.0 Data Analysis

4.2 Effect of Assumption of Exponential Failure Times

4.2.1 COMPUTER SIMULATION

Since most of the failure data collected for nonelectronic parts assumed constant failure rates (even though substantial evidence indicates otherwise) a study was made of the effects on reliability estimates made using the exponential assumption when other distributions more properly describe part failure times.

The objective of this analysis task was to investigate the effect on reliability estimates of using the assumption of exponentially distributed failure times when other distributions are better descriptors of nonelectronic part failure times. The reason for this interest is based on the ease of computations associated with such an assumption. On the other hand, if the method introduces serious error, it was felt it should not be considered.

The evaluation was accomplished by calculating confidence limits using the usual χ^2 methods for a hypothesized MTBF and comparing the width of the interval so calculated with one constructed using a computer simulation program to generate distributions of sample means for three non-exponential distributions. The general steps carried out in the simulation are outlined on the facing page.

The mean, θ, of the failure distribution (i.e., the MTBF) was chosen as the basis of comparison between the exponential and non-exponential distributions. For the exponential distribution, it is known that $2n\hat{\theta}/\theta$ (where the sample mean $\hat{\theta} = \frac{\sum T_i}{n}$ is based on a sample size n from a distribution with mean θ) is distributed as χ^2_{2n} for failure truncated data and χ^2_{2n+2} for time truncated data. For certain non-exponential distributions with mean θ, however, the distribution of the sample means cannot be obtained analytically; hence, computer simulation was necessary.

In the computer program, random failure times T were drawn in groups of n and $\sum_{i=1}^{n} \frac{T_i}{n}$ was computed as a sample mean for each group; 1000 such sample means were generated and then ordered. The first 50 and the last 50 values were then examined as good approximations of the tails of the distributions of sample means. The .05 and .95 percentile points were plotted in order to compare the widths of the 90% confidence intervals in the exponential case with the Weibull, lognormal, and gamma distributions. Specific results with each distribution are discussed in the 3 topics which follow.

General Steps in Computer Simulation

- Select n random values of $F(t)$
- Calculate n failure times
- Combine the failure times to calculate a Θ (MTBF)
- Repeat the above 3 steps 1000 times
- Printout the first 50 and the last 50 values obtained to establish 90% CONFIDENCE INTERVAL

4.0 Data Analysis

4.2 Effect of the Exponential Assumption

4.2.2 WEIBULL FAILURE TIMES

Because many nonelectronic parts exhibit failure times in accordance with the Weibull distribution with shape parameter greater than 1, the use of the assumption of exponential failure times as an approximation results in optimistic estimates.

Since the mathematical methods and calculations associated with the use of the exponential distribution in reliability analyses are so simple, it seems logical to employ these methods wherever possible. This phase of the study therefore was directed toward a general evaluation of the consequences of assuming exponentially distributed failure times when the true underlying distribution of failure times is Weibull.

The simulation was performed utilizing the following relationships. The cumulative distribution function (F) of a Weibull distribution with scale and shape parameters α and β respectively is given by the following equation:

$$F(t) = 1 - e^{-\frac{t^\beta}{\alpha}}$$

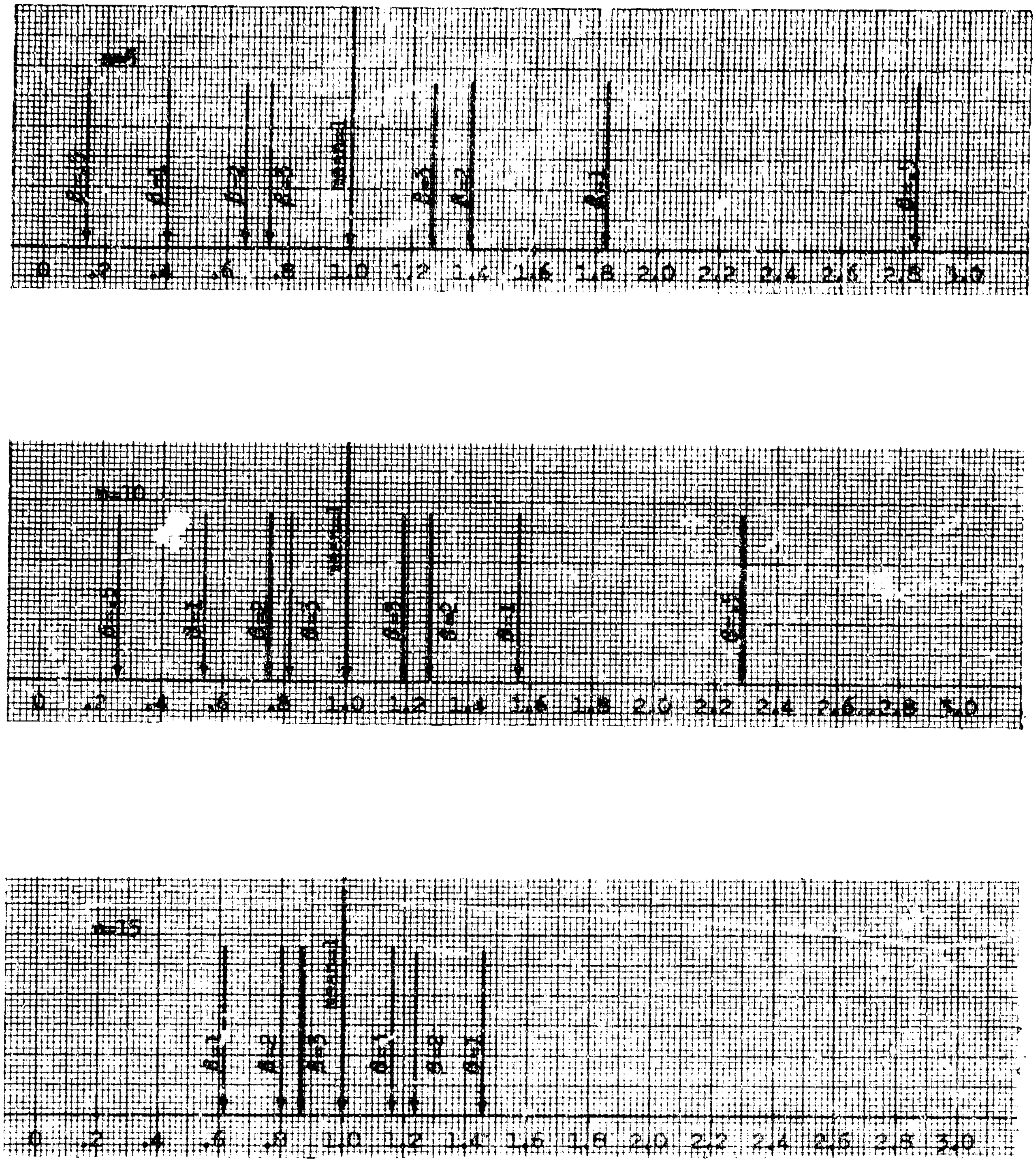
Since F is distributed uniformly on the interval $[0,1]$, random Weibull values of t can be generated by drawing uniform random numbers F from $[0,1]$ and equating

$$t = \alpha^{1/\beta} \left(\ln \frac{1}{1-F}\right)^{1/\beta}$$

The failure times so generated were combined in sample sizes of 5,10, and 15 and MTBF's were thus calculated for Weibull shape parameters (β) of .5, 1 (the exponential case), 2, and 3. The 90% limits generated for each case in the simulation program are compared in the charts on the facing page. It can be seen that when β is greater than 1 the Weibull confidence limits are narrower than the exponential limits. This indicates that substitution of the exponential assumption as an approximation for the Weibull results in a less accurate estimate of the true MTBF.

For example, suppose that a part has a Weibull failure distribution with $\beta=3$, and that 5 failure times are to be observed to test the hypothesis that the MTBF is 1000 hours. Note in the figure opposite that under the exponential assumption one would accept the hypothesis with 90% confidence if the sample MTBF lay between 394 and 1830 hours. However, with the knowledge that the failure distribution was Weibull with $\beta=3$, one would accept the hypothesis at the 90% confidence level only if the sample MTBF lay between 738 and 1270 hours. Hence, using the exponential assumption, one would accept the hypothesis with sample means which would cause rejection using the Weibull with $\beta=3$.

The result of this analysis demonstrates that in the case of nonelectronic parts whose failure times are distributed according to the Weibull with increasing hazard rates ($\beta > 1$), the use of the exponential as an approximation results in an optimistic estimate of the true MTBF.



90% Confidence Intervals on Sample MTBF's
Weibull Distribution

4.0 Data Analysis

4.2 Effects of the Exponential Assumption

4.2.3 LOGNORMAL FAILURE TIMES

Assuming that failure times are distributed exponentially introduces prediction and estimation errors when the failure times are really distributed as lognormal.

The tails of the distributions of sample means were examined and comparison was made at 90% confidence interval widths derived from the exponential and lognormal distributions of failure times.

The cumulative distribution of the lognormal is given by the following equation:

$$F(t) = \int_{0}^{t} \frac{1}{\sigma_x\sqrt{2\pi}} \exp\left(\frac{-(\ln x-\mu)^2}{2\sigma^2}\right) dx. \qquad (1)$$

In order to simulate the distribution of sample means from the lognormal distribution, it was noted that if $y = \log x$ is normally distributed (μ_y, σ_y), then x is lognormally distributed and its parameters (μ_x, σ_x) can be found in terms of (μ_y, σ_y). Also, a simple relationship exists between the quantities of the lognormal distribution (μ_x, σ_x) and the standard normal distribution. If ξ_q and v_q represent the values of x and y respectively for the q^{th} quantile, then

$$\xi_q = e^{\mu_y + v_q\sigma_y} \qquad (2)$$

Thus, to generate a random failure time from a lognormal distribution with parameters (μ_x, σ_x), the corresponding normal parameters are calculated

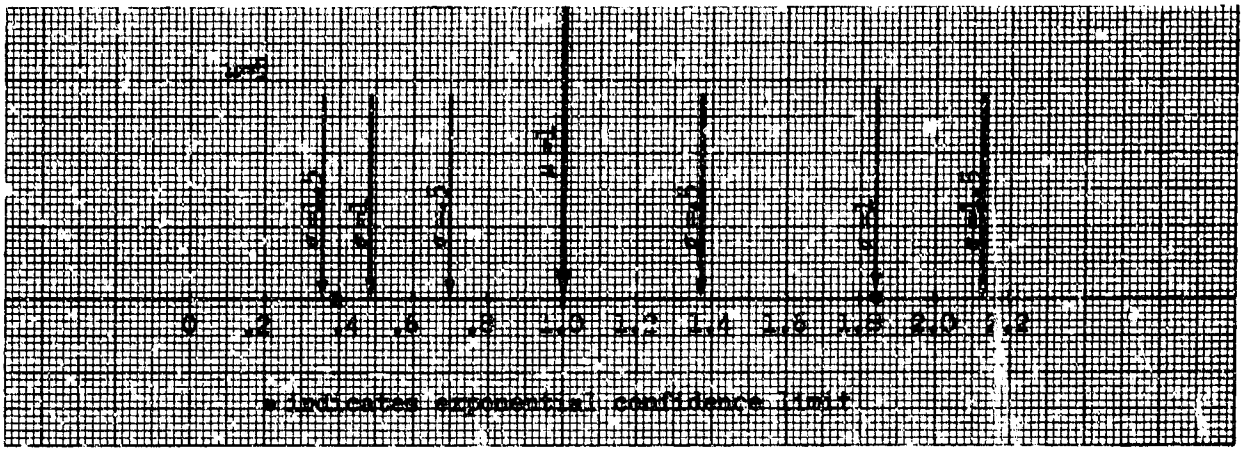
$$\mu_y = \log \frac{\mu_x^2}{\left[\sigma_x^2 + \mu_x^2\right]^{1/2}} \qquad (3)$$

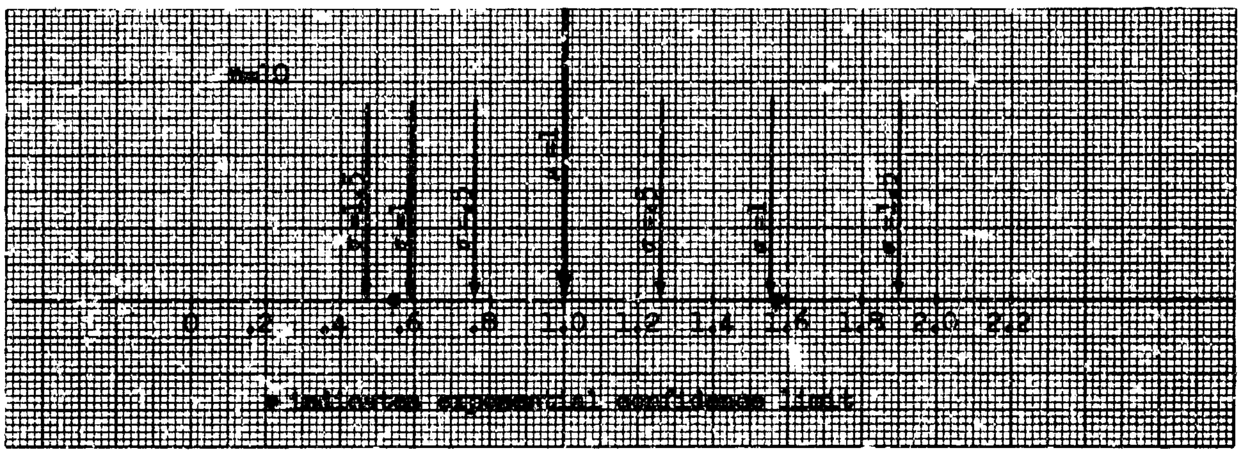
and

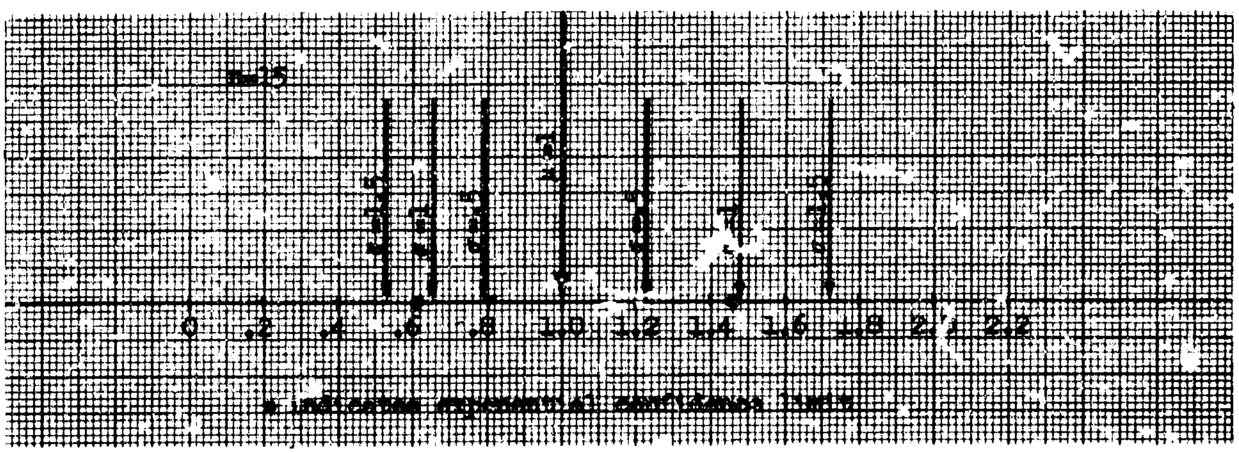
$$\sigma_y = \left(\log \frac{\sigma_x^2 + \mu_x^2}{\mu_x^2}\right)^{1/2} \qquad (4)$$

Then a random number between 0 and 1 is drawn, and from it a value of v_q is determined by linear interpolation from a table of 100 standard normal deviates stored in the memory of the computer. A random failure time is then generated by the transformation (2). Random failure times so generated are used to simulate sample mean distributions for various sample sizes as described in Topic 4.2.1.

For a standardized lognormal mean $\mu_x = 1$, 90% confidence interval widths are determined as a function of σ_x and n. Sample means were generated for $\sigma_x = 1/2, 1, 1\text{-}1/2$ for each of sample sizes n = 5, 10, 15. Although in this case the exponential is not a special case of the lognormal, whether the exponential confidence interval is too wide or too narrow for effective employment depends roughly upon whether σ is less than or greater than 1, as the figure opposite illustrates.







90% Confidence Intervals on Sample MTBF's

Lognormal Distribution

4.0 Data Analysis

4.2 Effects of the Exponential Assumption

4.2.4 GAMMA FAILURE TIMES

The exponential assumption applied to gamma failure times is responsible for errors in prediction and estimation of failure statistics.

The gamma cumulative distribution is given by

$$F(t) = \int_0^t \frac{1}{\Gamma(\alpha)\,\beta^{\alpha}}\, x^{\alpha-1}\, e^{-x/\beta}\, dx \qquad \alpha, \beta > 0$$

With the parameter β standardized to 1, the width of the relative 90% confidence limits for the sample mean distributions are determined by the parameter α. To sample random failure times from gamma distributions with $\alpha = 1,2,3$, and $\beta = 1$ in each case, it is noted that when α is an integer ≥ 1, the cumulative distribution function is given in the closed form

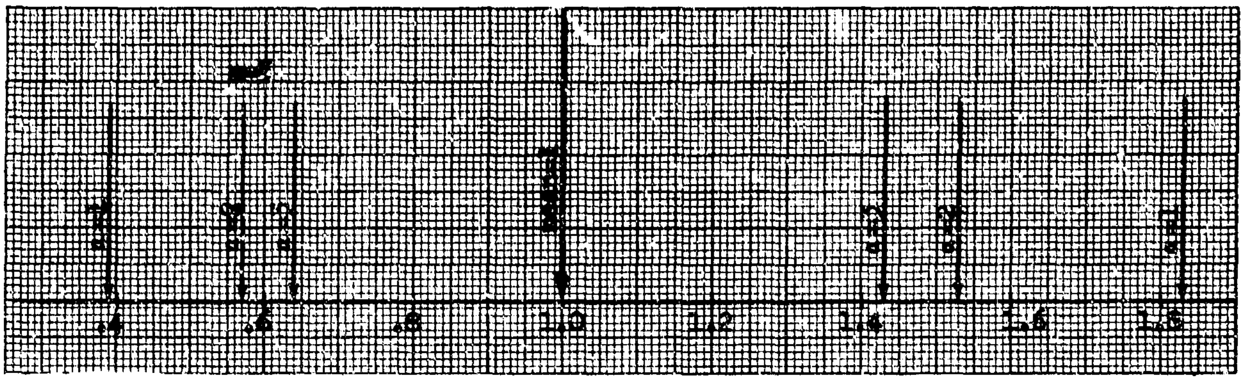
$$F(t) = 1 - \left[1 + t + \frac{t^2}{2!} + \cdots \frac{t^{\alpha-1}}{(\alpha-1)!}\right] e^{-t}$$

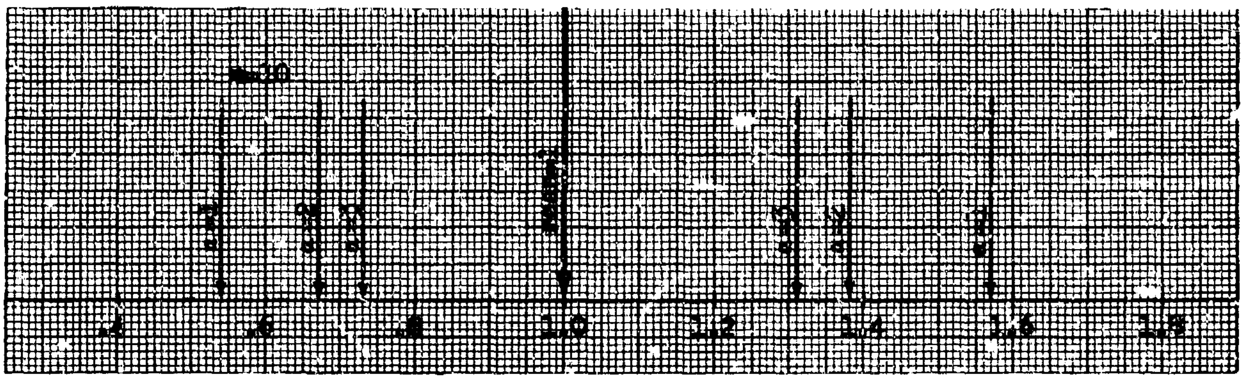
For example, to sample a random failure time from a gamma distribution with parameters $\alpha=3$, $\beta=1$, a random number F between 0 and 1 is first selected. Since the c.d.f. is uniformly distributed, a random failure time is obtained by solving

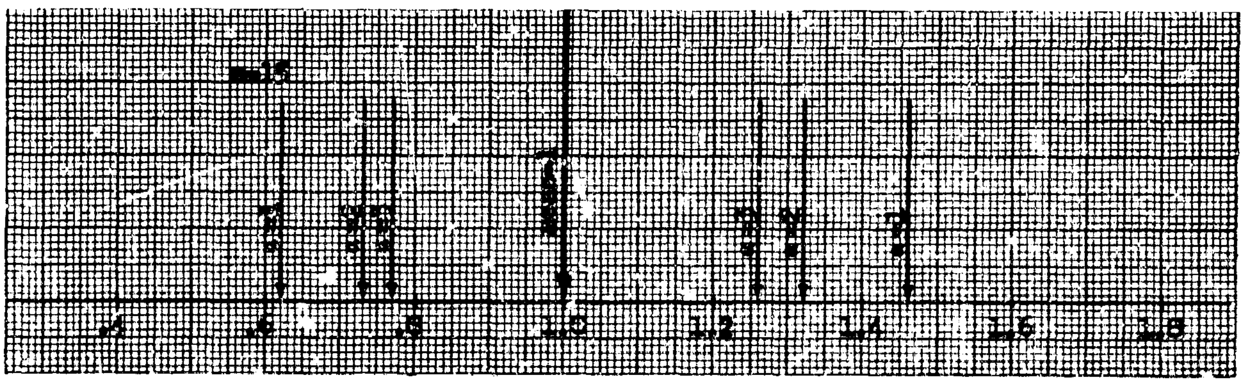
$$1 - F - (1 + t + \frac{t2}{2})\, e^{-t} = 0$$

The equation has no explicit solution, but Newton's algorithm is quickly implemented in the computer program to solve for t implicitly. Using the randon failure times generated, distributions of sample means are simulated as described in previous topics.

Distributions of sample means from gamma distributions with $\beta=1$, and $\alpha=1,2$, and 3, were simulated, using sample sizes n=5, 10, 15. Note that the case $\alpha=1$ is the exponential. The figure opposite shows that the confidence interval decreases as α increases, thus indicating that use of the exponential assumption gives confidence intervals too wide for parts with gamma failures and $\alpha > 1$.







90% Confidence Intervals on Sample MTBF's

Gamma Distribution

4.0 Data Analysis

4.3 Combination of Data

To organize this diverse mass of failure information into a useful tool, similar pieces of data were combined to yield overall failure rates for given part types when used in a similar environment and to increase the accuracy of the estimate.

To present the user of this bank of reliability data on nonelectronic parts with a mere listing of each failure rate estimate collected during the study would confront him with an unnecessarily confusing mass of information. He would have several estimates of the failure rate for a given part, each of which was an estimate of the true failure rate subject to sampling error. If like pieces of data could be combined then a more accurate estimate of the true parameter of interest could be generated.

It would be appealing to combine only failure information that was from parts of exactly the same type, used in exactly the same application, and exposed to exactly the same environmental stresses. On the other hand, it seems logical that the reliability characteristics of parts that are of the same generic type should be quite similar. Therefore, it would be ideal to combine as many of the pieces of data which were collected from a major generic part type to enhance the accuracy of the estimation and to provide an overall measure of reliability when the observed differences are not statistically significant.

The rules developed and used for combining failure data were based on engineering judgment, the number of pieces of failure data for a given part type in a given environment, and the completeness of the nomenclature of the part in the failure reports received. The first step was to pick out several high usage parts and divide the bank of failure data on each given generic part into several logical sub-part types. For example, electronic circuit connections were subdivided into crimped, soldered, welded and wire wrap categories. The data on each of these was then grouped by environmental application. At this point in the data analysis, 99% confidence limits were calculated for each piece of failure data. An example of this procedure is shown on the facing page. Ten failure reports were available on thermostats used in a ground environment. The confidence limits were then compared for each of the ten pieces of failure data. The decision as to which pieces of data to combine to calculate an overall failure rate was made by inspecting the span of the individual confidence intervals. As long as there was any degree of overlap and as long as there was continuity starting from the lower confidence limit of the failure report with the lowest failure rate, then all these failure reports were deemed to be combinable. Where a break occurred in the confidence intervals, it was felt that this was sufficient evidence that these were pieces of data from parts with significantly different failure rates and hence they should not be combined. To again refer to the example on the facing page, note that failure report number 3 covers the span from 0 to .913636 failures per million hours. Therefore, failure reports 2, 9, and 10 are combinable with it since they are within its limits. Then the confidence interval of failure report 5 partially overlaps that of number 3 by going from .082182 to 5.89971 failures per million hours. Also, the confidence intervals of failure reports 6 and 7 partially overlap the group already combined and they also include that of failure report number 8.

However, the confidence intervals of failure report number 1 and that of report number 4 are completely separated from the intervals enclosed by the other eight confidence intervals. The data sources of these outliers were used in attempting to determine more detail regarding differences of part type, test conditions or some other distinguishing detail that would account for the different failure rates. At any rate the majority of line entries (in this case all but 1 and 4) dictated which pieces of failure data would be combined to yield the overall failure rate. For thermostats, for example, the part hours of the 8 combinable failure reports were totalled as well as their failures and an overall failure rate of 4.08 failures per million hours was calculated. To this was added 90% confidence limits for the benefit of the user of the failure data.

This same procedure was used for combining data to calculate overall failure rates for 60 generic parts and sub-parts by their use environment. The complete list of failure rates and confidence limits by use environment is presented in Appendix Subsection 7.7.

<u>Example of Rules Used for Combining Individual Line Entries of Data to Yield an Overall Failure Rate</u>

Step 1: Calculate 99% Confidence Limits for all line entries of failure data for Thermostats (Ground Environment).

		Lower 99% Confidence Limit	Upper 99% Confidence Limit	Failure Rate (Failures per Million Hours)
Omit	~~1.~~	~~360.113~~	~~1783.15~~	~~916.666~~
	2.	0	.00797936	0
	3.	0	.913636	0
Omit	~~4.~~	~~48.2643~~	~~1324.83~~	~~428.571~~
	5.	.082182	5.89971	1.588
	6.	4.94732	20.2451	11.1164
	7.	4.94732	20.2451	11.1164
	8.	1.22034	11.2353	4.76417
	9.	0	.00797999	0
	10.	0	.00797999	0

Step 2: Omit any line entries whose Confidence Intervals do not, at least partially, overlap those of the majority of the line entries.

Step 3: Combine the operating hours and numbers of failures of the remaining line entries of failure data and calculate an overall failure rate and 90% confidence limits.

Failure Rate = 4.08 failures per million hours.
Upper 90% Confidence Limit = 5.39.
Lower 90% Confidence Limit = 3.13.
Total Part Hours = 8,826,900.
Total Number of Failures = 36.

4.0 Data Analysis

4.4 Environmental Differences in Failure Rates

4.4.1 CALCULATION OF K FACTORS

Since the data when grouped displayed significantly different failure rates for given part types over various environmental applications, k factors were developed to reflect this effect of environment on failure rate.

In dealing with failure data from electronic parts it is common practice to use conversion factors to estimate failure rates at a more severe environment. For the case of failure times distributed according to the exponential distribution, this conversion factor (k) becomes a simple multiplication factor.

In the present data collection effort there is evidence that many nonelectronic parts do not exhibit constant hazard rates with time. However, the present state of the art of data collection does not provide data that is detailed enough in nature to yield individual part failure times. Therefore, the k factors presented on the facing page represent "statistical differences" between grouped failure rates for selected parts using the assumption of exponential failure times. This method of calculating conversion factors is dictated by the type of data available.

It may be noted that the conversion factors shown on the facing page feature the "Airborne Application" as the base. This is accomplished by assigning a k factor of 1 to all airborne failure rates. This is a necessary, although a somewhat unconventional practice, since approximately 80% of the failure data collected on nonelectronic parts is from the airborne environment. This was therefore the only environment on which failure data was available on the overwhelming majority of parts and this made it the logical choice for use as a base.

The k factors presented display the expected relationships to one another with but few exceptions. Helicopter failure rates due to the characteristics of their severe vibration environment are generally higher than those for airborne applications as shown by k factors greater than 1. The k factors for ground and laboratory applications are generally lower than airborne as expected. The inconsistencies in the table wherein laboratory failure rates for soldered and wire wrap connections appear to be higher are due to accelerated life tests performed in the laboratory. In the case of valves the ground environment appears to be more severe than air but this data is dominated by failure reports from static test firings of missile motors.

A special rule was used in generating k factors for environments where no failures were observed. Upper one sided 90% confidence limits were calculated in these cases and the midpoint between zero and this limit was used as a point estimate. An example of this is shown in the table on the facing page. Ball bearings in the air environment have a failure rate of 6.44 failures per million hours. This part type used for 546,980 hours in the ground environment displayed no failures. The upper one sided 90% confidence limit was 4.21 failures per million hours. The midpoint between 0 and 4.21 was 2.1. Then 2.1 divided by 6.44 yields a k factor of .3 as shown in the facing table.

ENVIRONMENTAL APPLICATION FACTORS

	Air Failure Rate	Ground	Laboratory	Helicopter	Ship	Storage	Air, Ground	Sim. Air	Submarine	Missile
Actuators										
Hydraulic	378.58	.02		.4						
Bearings										
Ball	6.44	.3			.001		.7	1		
Capacitors, Variable										
Ceramic	21.06							1	1	
Glass	10.75	1				.01		1		
Connections										
Soldered	.035	.1	8		.2					
Welded	.052	.1	1							
Wire Wrap	.012	1	21							
Connectors										
Circular, Multipin	.98	1	.4				.1	1		
Coaxial	2.70	.2	.1					1	34	
Rectangular	22.20	.0004	.01					.04		
Generators										
AC	1120			.4		.0002				
DC	480.49			.4			2			
Gyros										
Free-Directional	1430			2			1			
Free-Vertical	1298						1.4			
Integrating	368.42	1	1							
Rate	351.23	.5	.2	1			12			
Pumps										
Electrically Driven	321.12		.7				8			
Engine Driven	664.93						4			
Fuel or Booster	170.43	1		1						
Hydraulic	808.87	.002		.5		.0001				22
Vacuum	770.64	1								
Relays										
Armature	16.61	.8	.3	1	.4	.003		1.5		
Contactor	9.50	.1								
Rotary	73.33								1	
Thermal	200	.1				.01	1	.2		
Time Delay	27.17	.5	.1		.5		1	1	.02	
Resistors, Variable										
Composition	18.61	.4	.01				2	.5		
Film	5.34		1				1			14
Wirewound	9.94	.3	.1		.02	.01	1	6		34
Seals										
Rotary	27.55			11						
Stationary	67.58	.3		1						
Switches										
Pushbutton	21.39	.01	.1			.1		1		
Rotary	17.04	.1	.1			1	1		25	
Snap-Action	15.33	.1	.1			.2		1		16
Toggle	6.91	.1	.1				1	1		
Synchros										
Control Resolver	139.72	.2		3	1		1	.01		
Control Transformer	2.05								.1	
Control Transmitter	.649							.3		
Tanks										
Compressed Gas	164.75	3								
Fuel Cells	160.78			1						
Reservoirs	74.30			9						
Thermostats	258.21	.02	.04				.02			
Transducers										
Pressure	848.57	1								
Temperature	93.32				1		3			
Valves										
Check	40	8	.2							
Control	138	13								
Relief	45	16								
Shutoff	88.7			2						
Solenoid	82			2						

4.0 Data Analysis

4.4 Environmental Differences in Failure Rates

4.4.2 STATISTICAL TESTS OF SIGNIFICANCE

Statistical tests of significance were employed to compare the observed differences in overall failure rates for given part types operated in the various environments.

When the grouped failure rates for a given part type used in several different environments were compared, the differences observed were not always large. Therefore, it was necessary to employ statistical tests of significance to determine if the differences could be construed to have occurred by chance or if they resulted from true differences in the life characteristics of the nonelectronic parts of interest when they were subjected to separate environmental applications.

The test of significance used, takes advantage of the fact that if two failure rates being compared are constant but not necessarily equal then

$$\frac{2T_1\hat{\lambda}_1}{2T_2\hat{\lambda}_2} \longrightarrow \frac{\chi^2_{2r_1+2}}{\chi^2_{2r_2+2}} = C$$

That is $\frac{2T_1\hat{\lambda}_1}{2T_2\hat{\lambda}_2}$ is distributed as the ratio of two χ^2 random variables with $2r_1+2$ and $2r_2+2$ degrees of freedom respectively. These degrees of freedom were used because it was reasoned that the data collected in this study was more likely to have been generated in time truncated tests rather than in failure truncated operation.

Then under the null hypothesis that $\lambda_1 = \lambda_2$, C is distributed as the F distribution with $2r_1 + 2$ and $2r_2 + 2$ degrees of freedom where r is the observed number of failures, and it may be used as a test of significance between failure rates.

The facing page shows an example of the results of the tests of significance. Failure rates of welded connections from ground and air applications were compared. The ratio of λ_{ground} to λ_{air} is the F ratio of .04 in this case. To determine if significance exists the F ratio must be compared to a value from a table of the F distribution for 10 and 20 degrees of freedom. Since the ratio of the failure rates is less than 1, the $F_{.05}$ value from the table (.36 in this example) is not to be exceeded in order to observe a significant difference between the two failure rates. Since .04 < .36 it may be said that the ground failure rate is significantly less than that of air at the $F_{.05}$ level of significance.

EXAMPLE OF F TEST FOR DETERMINING IF NONELECTRONIC PARTS EXHIBIT STATISTICALLY DIFFERENT FAILURE RATES IN DIFFERENT ENVIRONMENTS

Part Type: Connections, Welded

λ_{GROUND} = .0022 failures/million hours.

λ_{AIR} = .052 failures/million hours.

Number of Failures (Ground) = 4 Degrees of Freedom (Ground) = 10

Number of Failures (Air) = 9 Degrees of Freedom (Air) = 20

	F Ratio	$F_{.05}$
$\dfrac{\lambda_{GROUND}}{\lambda_{AIR}} = \dfrac{.0022}{.052} =$	.04	.36

Since .04 < .36, then the failure rate for welded connections in the ground environment is significantly less than the failure rate for the same type of connection used in air applications

4.0 Data Analysis

4.5 Testing Prediction Models

4.5.1 REGRESSION MODELS

Since there is evidence that the statistical methods required for use on nonelectronic parts are more complex than those conventionally used for electronic parts, a search was made for regression models with demonstrated usefulness in the prediction of the life characteristics of nonelectronic parts.

The search for prediction models useful for nonelectronic parts was successful in finding models which had proved valuable in estimating the life characteristics of relays and switches. This topic and the two subsequent topics discuss briefly the models, their use and degree of validation but refer to the reference documents for detailed descriptive information.

Perhaps the most successful model appears to be that described in Reference 19. It is basically a regression model of the form

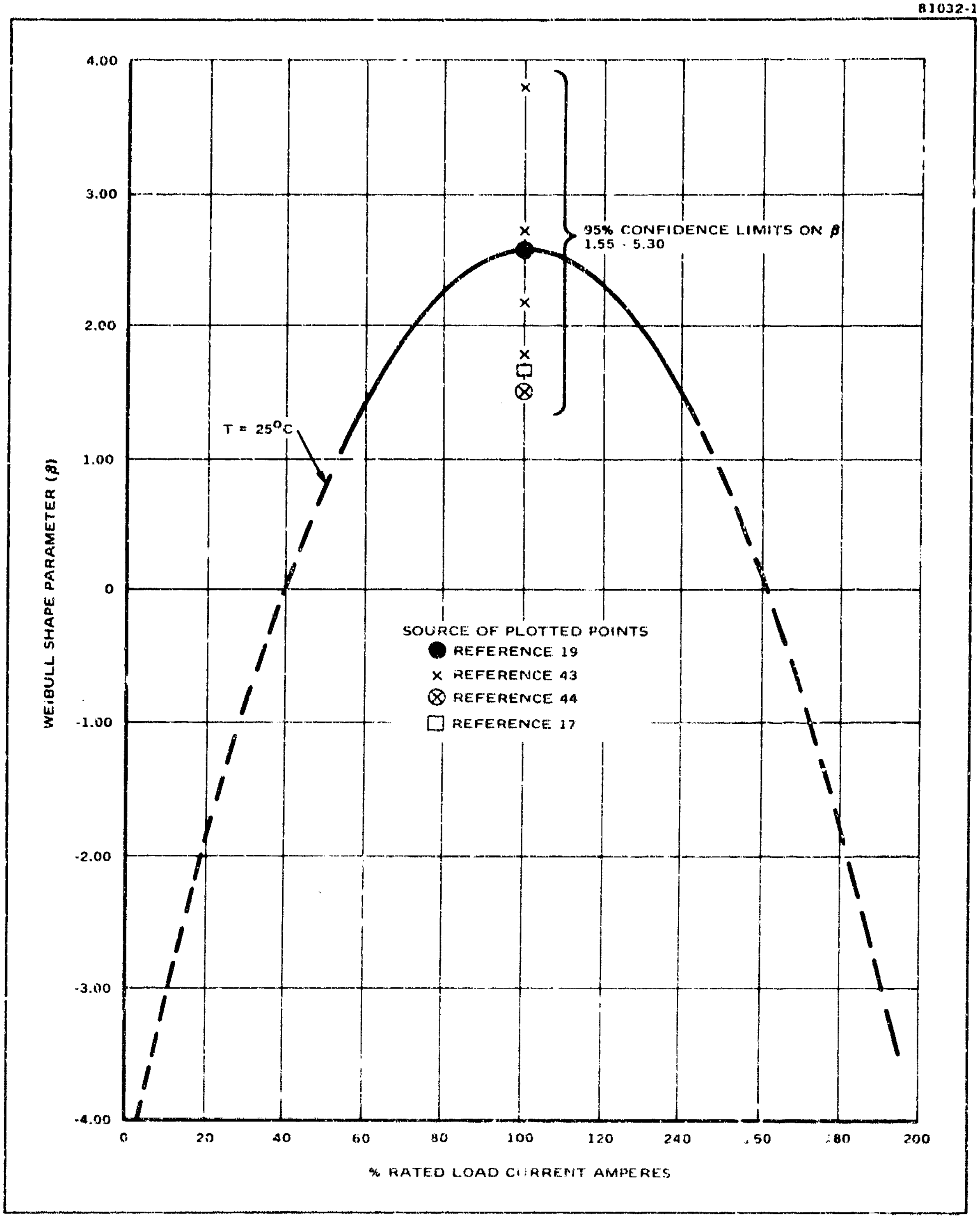
$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$$

where Y = the Weibull parameter of interest

x = the various operating or environmental stresses applied.

The model was developed by performing a central composite factorial design on several different relay designs. The tests were run with varying values of contact current, actuation rate, and ambient temperature applied in combination. All other factors were held constant. The observed failure times were distributed as Weibull with the general consensus of an increasing hazard rate. Regression equations were calculated on the Weibull shape and scale parameters. These were then converted to stress versus Weibull parameter curves. One such curve is shown on the facing page.

It was thought advisable to compare any relay data collected during this study with this model for general agreement. Therefore, six pieces of failure information on relays were found with enough detail as to operating and environmental conditions to warrant a comparison with the present model. The six points are plotted on the sample curve on the facing page. Confidence limits were calculated by computer simulation methods and did not show significant differences in the Weibull parameter estimates The strongest argument in favor of the model for further consideration is the fact that two separate tests on the exact same relay type yielded results which agreed closely. It might be possible that differences in relay design, or manufacturer would result in slightly different expressions for the regression equations but it is expected that the same general methodology could be used in developing the proper equations. The general model could perhaps be useful for other nonelectronic parts with Weibull failure times and increasing hazard rates.



Relay Data Compared to Regression Model for Weibull Shape Parameter (β) at 60 C.P.M. (Reference 19)

4.0 Data Analysis

4.5 Testing Prediction Models

4.5.2 TIME TRANSFORMATION MODELS

A prediction model based on the conventional k factor approach used for electronic parts has been shown to be useful in estimating the life characteristics of relays.

The models of interest in this topic were fully described in RADC TR 65-46 "Accelerated Reliability Test Methods for Mechanical and Electromechanical Parts." There they were used for predicting life characteristics of relays and switches at rated operating and environmental conditions from tests performed at overstress conditions. Contact current, ambient temperature, and actuation rate applied in combination were the accelerating stresses.

The failure times of the relays tested were distributed according to the Weibull with an increasing hazard rate. Three models were tested to predict part life characteristics at other stress levels. The conversion algorithms for the three models are shown in tabular form at the top of the facing page. The symbols in the algorithms are defined in Appendix 7.1. Weibull shape and scale parameters from parts tested at one set of combined stresses are used in the algorithms to predict Weibull shape and scale parameters of the parts if they were to be operated at other stress levels.

In the present study, data was sought that could be used in the three models to determine if any of them were useful in the prediction of the reliability of nonelectronic parts. Exercising the models required failure information from tests performed on the same part type at two different combined stress levels from tests performed at two different time periods.

Data fulfilling these requirements was located in References 19 and 53. Identical tests were run in 1964 and in 1966 on Struthers-Dunn FC-215 relays at different stress combinations. Two sets of results from each test were tried in the three prediction models. The test conditions and the Weibull shape and scale parameter estimates used are shown on the facing page under the title "Inputs to Algorithms."

The observed Weibull parameter estimates were then compared with those calculated in each of the three models. Confidence limits were generated by use of a computer simulation program. The results shown at the bottom of the facing page indicate that Model #5, featuring a constant ratio of the hazard rates at different stress levels is validated while the others are not. Model #5 is, in fact, the classical k factor model used as a prediction model in the exponential case. The reason for the more complex algorithm is that the Weibull shape parameter is generally not equal to 1 for nonelectronic parts.

Algorithms

	$\tilde{\alpha}_N^*$	$\tilde{\beta}_N^*$
Model No. 2 Transformation on Cumulative Failure Distribution	$\tilde{\alpha}_N^* = \tilde{\alpha}_A^* \Big/ \left(\dfrac{\tilde{\alpha}_A}{\tilde{\alpha}_N}\right)^{\tilde{\beta}_A^*/\tilde{\beta}_A}$	$\tilde{\beta}_N^* = \dfrac{\tilde{\beta}_N}{\tilde{\beta}_A}\tilde{\beta}_A^*$
Model No. 4 Transformation on Hazard Rate	$\tilde{\alpha}_N^* = \dfrac{\tilde{\alpha}_A^* \tilde{\beta}_N^*}{\tilde{\beta}_A^*} \Big/ \left(\dfrac{\tilde{\alpha}_A\tilde{\beta}_N}{\tilde{\alpha}_N\tilde{\beta}_N}\right)^{\frac{\tilde{\beta}_A^*-1}{\tilde{\beta}_A-1}}$	$\tilde{\beta}_N^* = \left(\dfrac{\tilde{\beta}_N-1}{\tilde{\beta}_A-1}\right)(\tilde{\beta}_A^* - 1) + 1$
Model No. 5 Constant Ratio of Hazard Rates	$\tilde{\alpha}_N^* = \left(\dfrac{\tilde{\alpha}_N\tilde{\beta}_A}{\tilde{\alpha}_A\tilde{\beta}_N}\right)\dfrac{\tilde{\alpha}_A^*\tilde{\beta}_N^*}{\tilde{\beta}_A^*}$	$\tilde{\beta}_N^* = \tilde{\beta}_A^* + (\tilde{\beta}_N - \tilde{\beta}_A)$

Inputs to Algorithms:		Source
$\tilde{\alpha}_N = 7.57 \times 10^{21}$	$\tilde{\beta}_N = 4.15$	Reference 53 (10 amps, 5 cycles/min., 75°C)
$\tilde{\alpha}_A = 4.83 \times 10^{13}$	$\tilde{\beta}_A = 2.65$	Reference 53 (13 amps, 51 cycles/min., 125°C)
$\tilde{\alpha}_A^* = 1.21 \times 10^8$	$\tilde{\beta}_A^* = 1.54$	Reference 19 (13 amps, 51 cycles/min., 125°C)

New Normal Stress Weibull Parameter Estimates:

Observed		Calculated		
	Reference 19 (10 amps, 5 cycles/min., 75°C)	Model No. 2	Model No. 4	Model No. 5
$\tilde{\alpha}_{0.90}^*$	$= 1 \times 10^{31}$			
$\tilde{\alpha}_N^*$	70×10^{19}	6.99×10^{12}	6.6×10^{10}	2.4×10^{16}
$\tilde{\alpha}_{0.10}^*$	$= 6 \times 10^{13}$			
$\tilde{\beta}_{0.90}^*$	$= 5.90$			
$\tilde{\beta}_N^*$	$= 3.62$	2.41	2.03	3.04
$\tilde{\beta}_{0.10}^*$	$= 2.57$			

4.0 Data Analysis

4.5 Testing Prediction Models

4.5.3 RADC RELIABILITY NOTEBOOK, VOLUME II, RELAY MODEL

The model for predicting relay failure rate in the RADC Reliability Notebook, Volume II, requires further development of relative reliability grade level to extend the flexibility of its application.

The failure rate prediction models in the RADC Reliability Notebook, Volume II, RADC TR 67-108, were exercised using as much sufficiently detailed information as had been collected in NEDCO and the resulting failure rates were compared to those obtained from the actual testing. Data of sufficient quality, i.e., with known detailed part descriptors and operating parameters, were found for relays and switches, only two of the parts studied in the RADC Reliability Notebook, Volume II. The relay model is discussed below and the switch model in the next topic.

The failure rate prediction model for relays is given by the following equation:

$$\lambda_R = \lambda_b(\pi_L \times \pi_C \times \pi_E \times \pi_{cyc} \times \pi_F),$$

where λ_R = predicted relay failure rate

λ_b = basic failure rate dependent upon operating temperature and temperature rating of the relay

π_L - factor based on load and percent rated resistive load

π_C = factor based on quantity and form of contacts

π_E = factor based on conditions of environmental service

π_{cyc} = factor based on cycling rate

π_F = factor based on relay family type and construction.

Actually, two different relay equations exist since in the RADC Reliability Notebook, Volume II, differentiation is made with respect to reliability characteristics by giving different multiplicative factors for upper and lower limits of relay reliability grade. In the figure opposite and in the complete table of calculated results given in the Appendix Subsection 7.2, references to the upper and lower reliability grade levels are made by the superscripts U and L respectively, on certain factors in the model. In cases where the complete information demanded by the model was not provided by the data source, either operation at rated conditions was assumed or the limiting values for the factors in the equation was used. The effect produced is to make the upper reliability grade estimate of failure rate at least as low as the missing information could make it. And, of course, the lower reliability grade estimate of failure rate at least as high as the missing information could

make it. So, this conservative practice widens the gap between upper reliability grade and lower reliability grade estimates of failure rate.

The figure below presents a typical calculation of the factors in the relay model and the resulting failure rate prediction (in percent per thousand hours), obtained. Also given is the observed failure rate λ (in percent per thousand hours), from the source of the data. Data used to generate the numerical factors for this example came from the Hughes-conducted study, Accelerated Reliability Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR 65-46. No testing of the model could be performed with data on relays run at accelerated contact current since determination of the multiplicative factor π_L is limited in the Notebook by a maximum ratio of load to rated resistive load of 1.0.

One notes in the figure below that the dominant multiplicative factor in the prediction model is π_{cyc}, the factor determined by cycling rate. Particularly for high cycling rates does the predicted failure rate λ_R reflect the model's sensitivity to π_{cyc}; for, as the cycling rate increases, the gap between the upper reliability grade cycling rate factor, π^U_{cyc}, and the lower reliability grade cycling rate factor, π^L_{cyc}, widens so that a wide range between λ^U_R and λ^L_R is produced. In such cases of high cycling rate tests especially, unless one is certain that the relay he is using is of the upper or lower reliability grade, as defined by the Notebook, he must arbitrarily decide which value between the relatively widely separated predicted failure rate limits is applicable to his relay. Note that in the example given below, the ratio of λ^L_R to λ^U_R is 144. Certainly, it would be difficult to obtain a failure rate prediction for a relay which did not conform in its relevant data exactly to the Notebook definition of either the upper or the lower grade of reliability. A quantitative measurement of the degree of reliability grade of the relay is needed so that one may, with some authority, select a value between the upper and lower grade reliability level failure rate limits set by the Notebook.

λ is expressed in failures per million operating hours											
Factors in Prediction Equation											
λ_b	λ_L	π_C	π^U_E	π^L_E	π^U_{cyc}	π^L_{cyc}	π^U_F	π^L_F	λ^U_R	λ^L_R	Observed λ
.0025	5	3	1	2	3,600	129,600	5	10	67.5	9,720	2,042.4

Typical Calculation of Relay Failure Rate

4.5.4 RADC RELIABILITY NOTEBOOK, VOLUME II, SWITCH MODEL

The switch failure rate prediction model in the RADC Reliability Notebook, Volume II, requires development of a guide to relative part reliability grade to increase its utility.

NEDCO-collected data of sufficient detail in part description and operating conditions was used to exercise the relay and switch models in the Notebook. The relay model is discussed in the preceding topic and the switch model discussion is given below.

Only data on single-body type switches was tested in the Notebook model. The model for predicting single-body type switch failure rate is given by the following equation:

$$\lambda_{SW} = \lambda_b(\pi_{cyc} \times \pi_C \times \pi_E \times \pi_G)$$

where λ_{SW} = predicted switch failure rate

λ_b = base failure rate dependent upon switch construction type

π_{cyc} = factor based on on-off cycling

π_C = factor based on contact form and quality

π_E = factor based on conditions of environmental service

π_G = factor based on upper and lower reliability grade.

A typical comparison of the predicted failure rate and the observed one is given in the figure opposite. The source of the data used is the same as for the relay failure rate prediction example, Accelerated Reliability Test Methods for Mechanical and Electromechanical parts, Technical Report No. RADC TR 65-46.

Consideration for upper and lower limits of switch reliability grade in the model makes two different switch failure rate prediction equations. None of the test data was found to lie between the Notebook predicted limits. Still, the ratio of the higher estimate of failure rate to the lower one, $\lambda_{SW}^{L}/\lambda_{SW}^{u}$, given by the Notebook, is so large in every case as to suggest the need for some quantitative guide to selecting failure rate values between the limits set by the Notebook.

λ is expressed in failures per million operating hours								
Factors in Prediction Equation						λ^U_{SW}	λ^L_{SW}	Observed λ
λ_b	π^U_G	π^L_G	π_{cyc}	π_C	π_E			
.05	.07	36	4,200	1.75	1	2.57	1,323	2,124.3

Typical Calculation of Switch Failure Rate

4.6 Failure Mode Analysis

The failure mode information collected indicates that the predominant failure mode for most nonelectronic parts is relatively insensitive to application environment.

In soliciting failure information for this study on the reliability characteristics of nonelectronic parts many reports were collected that contained detailed failure mode data.

It was therefore decided to analyze this body of information to determine if there were significant changes of failure mode when a part type was used in a different application environment.

The tabulation on the facing page is a listing of the different nonelectronic part types on which failure mode information was collected coupled with the most frequently occurring reason for failure for each environment on which detailed information was available. The complete listing of every failure mode observed for each part type is presented in Appendix Subsection 7.12.

An analysis of the information on the facing page yields the overall conclusion that for the nonelectronic parts on which failure information is available, there appears to be no great difference in failure mode when the part is used in environmental applications of varying severity. This is probably a reflection of the fact that most nonelectronic parts are designed specifically for a given function in a specific piece of equipment as opposed to being off-the-shelf items specified for a wide range of uses. The designer for nonelectronic parts very likely also uses a larger factor of safety for specific part applications where he has a more personalized input to an equipment design.

There are specific instances of failure mode changes over environment which are evident in the information presented on the facing page. For example, relays fail most frequently because of open contacts in ground applications, while in high vibration applications such as helicopter, simulated missile, and laboratory (accelerated tests) the major cause of failure is arcing or unstable operation. Relay designers have attempted to remedy this situation by specifying bifurcated contacts so that at least one of the two contact surfaces can keep the circuit closed during high vibration applications. The failure reports on which these failure mode changes were based were not detailed enough to describe whether these contact configurations were used in the high vibration environments. It would appear, however, to be a reasonable design guideline for inclusion into the list of design tradeoffs when specifying relays for severe environments.

Switches display the same type of failure mode change as do relays in going from ground to high vibration applications. All the other nonelectronic parts on which failure mode data were collected were not greatly affected by environmental changes.

Part / Environment	Predominant Failure Mode
Bearings	
Air	Excessive Wear
Ground	Excessive Wear
Helicopter	Scored
Actuators	
Air	Leaking
Ground	Leaking
Helicopter	Leaking
Connectors	
Ground	Open/Intermittent
Missile	Mechanical Damage
Generators	
Air	Excessive Wear
Helicopter	Shorted
Pumps	
Air	Leaking
Ground	Leaking
Helicopter	Leaking/Improper Operation
Relays	
Ground	Open
Helicopter	Arcing
Lab	Drift/Unstable
Simulated Missile	Drift/Unstable
Resistors, Variable	
Ground	Drift
Simulated Air	Noisy
Switches	
Air	Mechanical Damage/ Failed to Operate
Ground	Open
Lab	Drift/Unstable/ Erratic
Simulated Missile	Drift/Unstable/ Erratic
Tanks	
Air	Leaking
Helicopter	Leaking
Thermostats	
Air	Output Low
Ground	Drift
Transducers	
Air	Out of Tolerance
Helicopter	Out of Tolerance
Lab	Open
Missile	Output out of Tolerance
Transmitters	
Air	Out of Tolerance
Helicopter	Mechanical Binding
Valves	
Air	Leaking

Predominant Failure Modes for Certain Part-Environment Combinations

Based on the data collected, there was insufficient evidence to establish the relationship between part failure rate and the environmental and operational stresses under which the parts operated.

Very few of the failure reports collected contained a sufficient amount of detail regarding environmental and operating conditions during the life of the part. Where this detail was present, these data were used to attempt to establish the rate of change of the observed failure rate as a result of operational or environmental variations.

Most of the part reliability information collected was presented as though the failure rate was constant over time. The efforts to establish stress versus failure rate were therefore made using this assumption with its attendant high risk of error. The failure rate was viewed as the dependent variable and the operating or environmental stress was treated as the independent variable. Computer programs were employed to establish the equation of the line or curve of best fit by the method of least squares. Linear fits were attempted with equations of the form $y = a+bx$ where y was the value of the dependent variable (in these cases, failure rate). Non-linear fits were attempted with curves of the form $y = ae^{bx}$ and $y = ax^{b}$. In cases where temperature was the independent variable the conversion was made to the reciprocal of absolute temperature for analysis as well as °C. No fits were attempted where less than five data points were available.

Failure rate and operating and/or environmental information were compared by these methods on the following parts: For relays failure rate versus ambient temperature and versus relative humidity were compared. For switches, failure rate versus percent of rated current, ambient temperature, and relative humidity were studied to determine if a relationship could be found. For fans, the effect on failure rate of operating temperature was evaluated.

Linear, exponential, and power fits were attempted for the above mentioned parts and stresses. The equations of best fit are shown on the facing page. Tests of significance using the ratio of the stress sum of squares and the residual mean square as fractiles of the F distribution indicated that none of the relationships were statistically significant.

The meaning of this is doubtless a reflection of the quality of the detail of the data which were collected and of the assumptions of exponentiality imposed by the manner of data collection rather than proof that no relationship exists between part life and stress level.

There is evidence in the literature that part life versus stress relationships can be successfully stated. References 17, 19, 43, 44 and 53 are examples of this methodology. The successful use of these methods requires the recording of individual part failure times at each of several stress levels.

	*F Ratio	$F_{.05}$
Relays		
Failure Rate Versus Temperature, n = 12		
Equations:		
Linear $y = 23.8 - .23x$	.05	4.96
Exponential $y = 7.9\exp(-.002x)$	.000	4.96
Power $y = 9.4x^{-.109}$	.012	4.96
Failure Rate Versus Relative Humidity, n = 7		
Equations:		
Linear $y = -25.3 + .96x$	.780	6.61
Exponential $y = 2.22\exp(.029x)$	.001	6.61
Power $y = .103x^{1.184}$	.840	6.61
Switches		
Failure Rate Versus Rated Current, n = 6		
Equations:		
Linear $y = 171.6 - 2.62x$	.172	7.71
Exponential $y = 73.3\exp(-.03x)$	.000	7.71
Power $y = 114.2x^{-.52}$	.001	7.71
Failure Rate Versus Temperature, n = 14		
Equations:		
Linear $y = 66.76 + .35x$	.005	4.75
Exponential $y = 29.46\exp(-.01x)$	.000	4.75
Power $y = 92.14x^{-.44}$	.000	4.75
Failure Rate Versus Relative Humidity, n = 8		
Equations:		
Linear $y = 489.6 - 5.76x$	.214	5.99
Exponential $y = 10.02\exp(.003x)$	.000	5.99
Power $y = 24.88x^{-18}$	.000	5.99

*F Ratio must exceed $F_{.05}$ for significance.

Summary of Failure Rate Versus Stress Equations

SECTION 5
CONCLUSIONS

5.0 Conclusions

The general conclusions based on the findings of this study are that much failure data is available on nonelectronic parts although its utility is open to question due to its lack of completeness.

The following is a summary of the specific conclusions based on this study program:

- 38,761 line entries of failure information on nonelectronic parts has been collected, classified, organized, stored on computer tape, and printed out in the Appendix of this report.

- Much more data is available on nonelectronic parts. It was encountered during the Data Search phase of this study but was in raw form and thus its collection would have been too costly for incorporation into this data bank at the present time.

- More failure data is required on certain part types and on certain environmental applications in order to yield more accurate estimates of the reliability characteristics on the whole spectrum of parts and application and to enrich the data base on nonelectronic parts.

- The statistical methods of reliability in general use for electronic parts must be augmented for use on nonelectronic parts whose failure times are distributed according to other than the exponential distribution.

- Three reliability pre tion models were tested for use with nonelectronic parts. Although none them were completely validated, each demonstrated enough promise that th t further investigation and refinement for development into useful s for nonelectronic reliability.

- The data collected during this study effort were not detailed enough to allow the establishment of the relationships existing between part life and operating and/or environmental stresses.

SECTION 6
RECOMMENDATIONS

6.0 Recommendations

The findings of this study together with other significant contributions to the field of nonelectronic reliability should be incorporated into a Handbook of Nonelectronic Reliability.

In addition to that stated above the following actions are presented as recommendations based on the findings of this study:

- Reliability data on nonelectronic parts must be collected with more detail regarding individual part failure times, part descriptions, and operating/environmental stresses.

- The reliability prediction models discussed in Subsections 4.5.1 through 4.5.4 should be the subject of study to complete their verification for use on switches and relays and their use should be extended if possible to other types of nonelectronic parts.

- More exact failure data should be generated and analyzed in order to establish the relationships existing between the life of the various nonelectronic part types and the operating and environmental stresses under which they are used.

- The current data base should be augmented by collecting more failure data on certain part-environment combinations.

SECTION 7
APPENDIX

Section 7.0 Appendix

Subsection 7.1 Algorithm for Calculating Life Expectancy at Manufacturer's Rated Stress Conditions $\tilde{\alpha}^*_N$, β^*_N

Model 2	$\tilde{\alpha}^*_N = \tilde{\alpha}^*_A \Big/ \left(\dfrac{\tilde{\alpha}_A}{\tilde{\alpha}_N}\right)^{\tilde{\beta}^*_A / \tilde{\beta}_A}$	$\tilde{\beta}^*_N = \dfrac{\tilde{\beta}_N}{\tilde{\beta}_A}\tilde{\beta}^*_A$
Model 4	$\tilde{\alpha}^*_N = \dfrac{\tilde{\alpha}^*_A \tilde{\beta}^*_N}{\tilde{\beta}^*_A} \Big/ \left(\dfrac{\tilde{\alpha}_A \tilde{\beta}_N}{\tilde{\alpha}_N \tilde{\beta}_A}\right)^{\frac{\beta^*_A - 1}{\beta_A - 1}}$	$\tilde{\beta}^*_N = \left(\dfrac{\tilde{\beta}_N - 1}{\tilde{\beta}_A - 1}\right)(\tilde{\beta}^*_A - 1) + 1$
Model 5	$\tilde{\alpha}^*_N = \left(\dfrac{\tilde{\alpha}_N \tilde{\beta}_A}{\tilde{\alpha}_A \tilde{\beta}_N}\right)\dfrac{\tilde{\alpha}^*_A \tilde{\beta}^*_N}{\tilde{\beta}^*_A}$	$\tilde{\beta}^*_N = \tilde{\beta}^*_A + (\tilde{\beta}_N - \tilde{\beta}_A)$

where:

$\tilde{\alpha}^*_N$ = estimate of Weibull scale parameter for parts if they had been tested at manufacturer's rated operating and environmental stresses

$\tilde{\beta}^*_N$ = estimate of Weibull shape parameter for parts if they had been tested at manufacturer's rated operating and environmental stresses

$\tilde{\alpha}^*_A$ = estimate of Weibull scale parameter obtained from a current test run at accelerated stresses

$\tilde{\beta}^*_A$ = estimate of Weibull shape parameter obtained from a current test run at accelerated stresses

$\tilde{\alpha}_N$ = estimate of Weibull scale parameters from a previous test run of parts operated at manufacturer's rated conditions.

$\tilde{\beta}_N$ = estimate of Weibull shape parameter from a previous test run of switches operated at manufacturer's rated conditions

$\tilde{\alpha}_A$ = estimate of Weibull scale parameter from a previous test run of switches operated at accelerated stress conditions

$\tilde{\beta}_A$ = estimate of Weibull shape parameter from a previous test run of switches operated at accelerated stress conditions.

Section 7.0 Appendix

Sub-Section 7.2 TESTING RADC RELIABILITY NOTEBOOK, VOLUME II, RELAY FAILURE RATE PREDICTION MODEL

Example 1

Data Source: Reliability Evaluation Report Model 410-26 Relay, Teledyne Precision, Inc., July 2, 1964.

Description: Relay is 125°C rated run at 125°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 1 cycle per second; balanced armature general purpose (0-5 amp).

λ is expressed in failures per million operating hours.

$\lambda_b = 0.0065$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1{,}296$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 102.4 \\ \lambda_R^L = 1{,}474 \end{array}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 207.4$

Example 2

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Reliability Testing for Nonelectronic Parts, Technical Report No. RADC-TR-66-425, 1966.

Description: Relay is 125°C rated run at 25°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 1 cycle per second; balanced armature general purpose (0-5 amp).

λ is expressed in failures per million operating hours.

$\lambda_b = 0.0011$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1,296$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 29.7 \\ \lambda_R^L = 427.7 \end{array}\right\} \lambda_R^L/\lambda_R^U = 14.4$$

Observed λ = 7,982 (Manufacturer A)
= 1,975 (Manufacturer B)
= 4,139 (Manufacturer C)
= 3,085 (Manufacturer D)

Example 3

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 25°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 1 cycle per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1,296$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{aligned} \lambda_R^U &= 29.7 \\ \lambda_R^L &= 427.7 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 5,327$

Example 4

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 100°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 1 cycle per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.0025$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1,296$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 67.5 \\ \lambda_R^L = 972 \end{array}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 5,304.6$

Example 5

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 150°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 1 cycle per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.03$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1{,}296$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{aligned}\lambda_R^U &= 810\\ \lambda_R^L &= 11{,}664\end{aligned}\right\}\lambda_R^L/\lambda_R^U = 14.4$$

Observed $\lambda = 4{,}064.4$

Example 6

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 25°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 10 cycles per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 3{,}600$

$\pi_{cyc}^L = 129{,}600$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{matrix} \lambda_R^U = 297 \\ \lambda_R^L = 42{,}768 \end{matrix}\right\} \lambda_R^L / \lambda_R^U = 144$$

Observed λ = 101,904

Example 7

Data Source: Schafer, R. and Turkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 100°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 10 cycles per second; balance armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.0025$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 3{,}600$

$\pi_{cyc}^L = 129{,}600$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 675 \\ \lambda_R^L = 97{,}200 \end{array}\right\} \lambda_R^L/\lambda_R^U = 144$$

Observed λ = 20,424

Example 8

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 150°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 10 cycles per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.03$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 3{,}600$

$\pi_{cyc}^L = 129{,}600$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{aligned} \lambda_R^U &= 8{,}100 \\ \lambda_R^L &= 1{,}166{,}400 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 144$$

Observed λ = 30,956

Example 9

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 25°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 30 cycles per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda b = 0.0011$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 10{,}800$

$\pi_{cyc}^L = 1{,}166{,}400$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 891 \\ \lambda_R^L = 384{,}912 \end{array}\right\} \lambda_R^L / \lambda_R^U = 432$$

Observed $\lambda = 965{,}414$

Example 10

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 100°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 30 cycles per second; balanced armature general purpose (0-5 amp).

λ is expressed in terms of failures per million hours.

$\lambda_b = 0.0025$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 10,800$

$\pi_{cyc}^L = 1,166,400$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l} \lambda_R^U = 2,025 \\ \lambda_R^L = 874,800 \end{array}\right\} \lambda_R^L / \lambda_R^U = 432$$

Observed λ = 469,763

Example 11

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Relay is 125°C rated run at 150°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 30 cycles per second; balanced armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.03$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 10,800$

$\pi_{cyc}^L = 1,166,400$

$\pi_F^U = 5.0$

$\pi_F^L = 10.0$

$$\left.\begin{array}{l}\lambda_R^U = 24,300 \\ \lambda_R^L = 10,497,600\end{array}\right\} \lambda_R^L / \lambda_R^U = 432$$

Observed λ = 608,572

Example 12

<u>Data Source:</u> Failure Rate Data (FARADA), June 1967

<u>Description:</u> Relay run at 85°C with resistive load at 100 percent rating; 6PDT contacts; operating in a laboratory environment at a cycling rate of 21 cycles per minute; sensitive (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 5.0$

$\pi_C = 8.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 126$

$\pi_{cyc}^L = 158.76$

$\pi_F^U = 2.0$

$\pi_F^L = 100.0$

$$\left.\begin{array}{l} \lambda_R^U = 65.5 \\ \lambda_U^L = 8{,}255.7 \end{array}\right\} \lambda_R^L / \lambda_R^U = 126$$

Observed $\lambda = 12{,}600$

Assumptions

1. 85°C rated relay.
2. Limiting values of π_F used, since construction type is unknown.

Example 13

Data Source: Failure Rate Data (FARADA), June 1967.

Description: Relay run at 52°C with resistive load at 0.05 percent rating; DPDT contacts; operating in a laboratory environment at 2 cycles per second; latching (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0015$

$\pi_L = 1.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 720$

$\pi_{cyc}^L = 5{,}184$

$\pi_F^U = 5$

$\pi_F^L = 20$

$$\left.\begin{aligned}\lambda_R^U &= 16.2\\ \lambda_R^L &= 933.1\end{aligned}\right\}\ \lambda_R^L / \lambda_R^U = 58$$

Observed $\lambda = 288$

Assumptions

1. 125°C rated relay
2. Limiting values of π_F used, since relay construction type is unknown.

Example 14

Data Source: Failure Rate Data (FARADA), June 1967.

Description: Relay run at 125°C with resistive load at 100 percent rating; operating in a laboratory environment at 22 cycles per minute; latching (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 5.0$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 132$

$\pi_{cyc}^L = 174.24$

$\pi_F^U = 5.0$

$\pi_F^L = 20.0$

$$\left.\begin{array}{l} \lambda_R^U = 21.5 \\ \lambda_R^L = 1{,}812.1 \end{array}\right\} \lambda_R^L / \lambda_R^U = 84.5$$

Observed $\lambda = 105.6$

Assumptions

1. 125°C rated relay.
2. Limiting values for π_C used, since relay contact form and quantity is unknown.
3. Limiting values for π_F used, since relay construction type is unknown.

Example 15

Data Source: Failure Rate Data (FARADA), June 1967.

Description: Relay run at 125°C with resistive load at 100 percent rating; operating in a laboratory environment at 22 cycles per minute; time delay (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 5.0$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 132$

$\pi_{cyc}^L = 174.24$

$\pi_F^U = 9.0$

$\pi_F^L = 12.0$

$\lambda_R^U = 38.6$

$\lambda_R^L = 1{,}087.3$

$\lambda_R^L / \lambda_R^U = 28.2$

Assumptions

1. 125°C rated relay.
2. Limiting values for π_C used, since relay contact form and quantity is unknown.

Observed $\lambda = 924$

Example 16

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 25°C with resistive load at 63 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 30 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 1.9$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 180$

$\pi_{cyc}^L = 324$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned} \lambda_R^U &= 1.97 \\ \lambda_R^L &= 14.2 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 7.2$$

Observed λ = 1.479

Assumptions

1. 125°C rated relay.

Example 17

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 25°C with resistive load at 63 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 120 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 1.9$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 720$

$\pi_{cyc}^L = 5.14$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$\lambda^U = 7.9$

$\lambda_R^L = 227.1$

Observed $\lambda = 2.047$

Assumptions

1. 125°C rated relay.

Example 18

<u>Data Source:</u> <u>Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models,</u> General Electric, Contract No. DA 36-039 SC-78937, June 1963.

<u>Description:</u> Relay run at 125°C with resistive load at 63 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 120 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.9$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 720$

$\pi_{cyc}^L = 5{,}184$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

Assumptions

1. 125°C rated relay.

$$\left.\begin{aligned} \lambda_R^U &= 46.7 \\ \lambda_R^L &= 1344.3 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 29$$

Observed $\lambda = 6{,}487$

Example 19

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 125°C with resistive load at 63 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 30 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.9$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 180$

$\pi_{cyc}^L = 324$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned} \lambda_R^U &= 11.7 \\ \lambda_R^L &= 84 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 7.2$$

Observed $\lambda = 779$

Assumptions

1. 125°C rated relay.

Example 20

<u>Data Source:</u> <u>Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models,</u> General Electric, Contract No. DA 36-039 SC-78937, June 1963.

<u>Description:</u> Relay run at 75°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 60 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1{,}296$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned} \lambda_R^U &= 15.1 \\ \lambda_R^L &= 217.7 \end{aligned}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 6{,}349$

Assumptions

1. 125°C rated relay.

Example 21

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 75°C with resistive load at 50 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 60 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 1.5$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1{,}296$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 4.5 \\ \lambda_R^L = 65.0\end{array}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 8{,}219$

Assumptions

1. 125°C rated relay.

Example 22

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 0°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 60 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.001$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1{,}296$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 9.5\\ \lambda_R^L = 136.1\end{array}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 3{,}114$

Assumptions

1. 125°C rated relay.

Example 23

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 150°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 60 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.03$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1,296$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 283.5 \\ \lambda_R^L = 4,082\end{array}\right\} \lambda_R^L / \lambda_R^U = 14.4$$

Observed $\lambda = 2,338$

Assumptions

1. 125°C rated relay.

Example 24

<u>Data Source:</u> <u>Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models</u>, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

<u>Description:</u> Relay run at 75°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 22 1/2 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 135$

$\pi_{cyc}^L = 182$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 5.67 \\ \lambda_R^L = 30.6\end{array}\right\} \lambda_R^L / \lambda_R^U = 5.4$$

Observed $\lambda = 210$

<u>Assumptions</u>

1. 125°C rated relay.

Example 25

Data Source: Final Technical Report Task II, Statistically Designed Experiment of Integral Capsular Relays, Single Pole Double-Throw Engineering Test Models, General Electric, Contract No. DA 36-039 SC-78937, June 1963.

Description: Relay run at 75°C with resistive load at 100 percent rating; SPDT contacts; operating in a laboratory environment at a cycling rate of 160 cycles per minute; armature general purpose (0-5 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 1.75$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 960$

$\pi_{cyc}^L = 9{,}216$

$\pi_F^U = 3.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 40.3 \\ \lambda_R^L = 1{,}548.3\end{array}\right\} \lambda_R^L / \lambda_R^U = 38$$

Observed $\lambda = 4{,}151$

Assumptions

1. 125°C rated relay.

Example 26

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 25°C with resistive load at 70 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 14 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 2.15$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 84$

$\pi_{cyc}^L = 84$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 1.19 \\ \lambda_R^L = 7.14\end{array}\right\} \lambda_R^L / \lambda_R^U = 6$$

Observed $\lambda = 1{,}954$

Example 27

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 25°C with resistive load at 70 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 51 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0011$

$\pi_L = 2.15$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 306$

$\pi_{cyc}^L = 936.36$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 4.33\\[1em] \lambda_R^L = 79.55\end{array}\right\} \lambda_R^L / \lambda_R^U = 18.4$$

Observed $\lambda = 5,276$

Example 28

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 125°C with resistive load at 70 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 14 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 2.15$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 84$

$\pi_{cyc}^L = 84$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 7.04 \\ \lambda_R^L = 42.2\end{array}\right\} \lambda_R^L / \lambda_R^U = 6$$

Observed λ = 1,750

Example 29

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 125°C with resistive load at 70 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 51 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 2.15$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 306$

$\pi_{cyc}^L = 936.36$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 25.6 \\ \lambda_R^L = 470.[illegible] \end{array}\right\} \lambda_R^L / \lambda_R^U = 18.4$$

Observed $\lambda = 3,558$

Example 30

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 75°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 32-1/2 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 195$

$\pi_{cyc}^L = 380.25$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 9.4 \\ \lambda_R^L = 109.5 \end{array}\right\} \lambda_R^L / \lambda_R^U = 12$$

Observed λ = 6,094

Example 31

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 0°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 32-1/2 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.001$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 195$

$\pi_{cyc}^L = 380.25$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 5.9 \\ \lambda_R^L = 68.4\end{array}\right\} \lambda_R^L / \lambda_R^U = 12$$

Observed λ = 8,864

Example 32

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 150°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 32-1/2 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.03$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 195$

$\pi_{cyc}^L = 380.25$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 176 \\ \lambda_R^L = 2{,}053 \end{array}\right\} \lambda_R^L / \lambda_R^U = 12$$

Observed $\lambda = 3{,}980$

Example 33

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2692, March 1966.

Description: Relay is 125°C rated run at 75°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 5 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 30$

$\pi_{cyc}^L = 30$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 1.4 \\ \lambda_R^L = 8.6\end{array}\right\} \lambda_R^L / \lambda_R^U = 6$$

Observed $\lambda = 1,580$

Example 34

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2697, March 1966.

Description: Relay is 125°C rated run at 75°C with resistive load at 100 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 60 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 5.0$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 360$

$\pi_{cyc}^L = 1,296$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 17.3\\ \lambda_R^L = 373\end{array}\right\} \lambda_R^L/\lambda_R^U = 22$$

Observed λ = 12,414

Example 35

Data Source: Fontana, W. J., Life Expectancy of a New Miniature Power Relay, Technical Report ECOM-2697, March 1966.

Description: Relay is 125°C rated run at 75°C with resistive load at 55 percent rating; DPDT contacts; operating in a laboratory environment at a cycling rate of 32-1/2 cycles per minute; balanced armature medium power (5-20 amp).

λ is expressed in failures per million hours.

$\lambda_b = 0.0016$

$\pi_L = 1.6$

$\pi_C = 3.0$

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 195$

$\pi_{cyc}^L = 380.25$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l}\lambda_R^U = 3.0 \\ \lambda_R^L = 35\end{array}\right\} \lambda_R^L / \lambda_R^U = 12$$

Observed $\lambda = 2{,}143$

Example 36

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966

Description: Relay is run with resistive load at 0.8 percent rating; single pole contact; operating in a laboratory environment at a cycling rate of 20 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 1.75)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 7{,}200$

$\pi_{cyc}^L = 518{,}400$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned}\lambda_R^U &= 93.6\\ \lambda_R^L &= 70{,}720\end{aligned}\right\}\ \lambda_R^L/\lambda_R^U = 756$$

Observed $\lambda = 14{,}930$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Example 37

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966.

Description: Relay is run with resistive load at 0.8 percent rating; operating in a laboratory environment at a cycling rate of 100 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 36{,}000$

$\pi_{cyc}^L = 12{,}960{,}000$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 468 \\ \lambda_R^L = 8{,}112{,}000 \end{array}\right\} \lambda_R^L / \lambda_R^U = 17{,}300$$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown
4. Vibrating reed application type.

Observed $\lambda = 135$

Example 38

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966.

Description: Relay is run with resistive load at 1 percent rating; operating in a laboratory environment at a cycling rate of 60 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 1.75)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 21{,}600$

$\pi_{cyc}^L = 4{,}665{,}600$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 281 \\ \lambda_R^L = 637{,}000 \end{array}\right\} \lambda_R^L / \lambda_R^U = 2{,}269$$

Observed $\lambda = 110$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Example 39

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966.

Description: Relay is run with resistive load at 2.4 percent rating; single pole contact; operating in a laboratory environment at a cycling rate of 60 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 1.75)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 21,600$

$\pi_{cyc}^L = 4,665,600$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned}\lambda_R^U &= 281\\ \lambda_R^L &= 637,000\end{aligned}\right\}\ \lambda_R^L/\lambda_R^U = 2,269$$

Assumptions

1. 125°C rated relay.
2. 125°C operating
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Observed $\lambda = 87$

Example 40

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966.

Description: Relay is run with resistive load at 0.4 percent rating; operating in a laboratory environment at a cycling rate of 60 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 21{,}600$

$\pi_{cyc}^L = 4{,}665{,}600$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{aligned}\lambda_R^U &= 281\\ \lambda_R^L &= 2{,}911{,}090\end{aligned}\right\} \lambda_R^L / \lambda_R^U = 10{,}367$$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Observed $\lambda = 152$

Example 41

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966

Description: Relay is run with resistive load at 0.8 percent rating; operating in a laboratory environment at a cycling rate of 20 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.0$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 7,200$

$\pi_{cyc}^L = \cancel{518,400}$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$\lambda_R^U = 93.6$

$\lambda_R^L = 323,291$

$\lambda_R^L / \lambda_R^U = 3,454$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Observed λ = 3,300

Example 42

Data Source: The Wheelock Relay Story, Wheelock Signal Inc., 1966.

Description: Relay is run with resistive load at 20 percent rating; operating in a laboratory environment at a cycling rate of 20 cycles per second; glass reed.

λ is expressed in failures per million hours.

$\lambda_b = 0.0065$

$\pi_L = 1.1$

$\pi_C =$ (limits are 1.0 and 8.0)

$\pi_E^U = 1.0$

$\pi_E^L = 2.0$

$\pi_{cyc}^U = 7{,}200$

$\pi_{cyc}^L = 518{,}400$

$\pi_F^U = 2.0$

$\pi_F^L = 6.0$

$$\left.\begin{array}{l} \lambda_R^U = 103 \\ \lambda_R^L = 355{,}619 \end{array}\right\} \lambda_R^L / \lambda_R^U = 3{,}454$$

Observed $\lambda = 1{,}359$

Assumptions

1. 125°C rated relay.
2. 125°C operating.
3. Limiting values of π_C used, since contact form is unknown.
4. Vibrating reed application type.

Section 7.0 Appendix

Sub-Section 7.3 TESTING RADC RELIABILITY NOTEBOOK, VOLUME II, SWITCH FAILURE RATE PREDICTION MODEL

Example 1

Data Source: Failure Rate Data (FARADA), June 1967.

Description: Switch is 4PDT push button run at a cycling rate of 20 cycles per minute; operating in a laboratory environment.

λ is expressed in failures per million hours.

λ_b = (limits are 0.05 and 0.1)

$\pi_{cyc} = 1{,}200$

$\pi_C = 5.5$

$\pi_E = 1.0$

$\pi_G^U = 0.2$

$\pi_G^L = 15.0$

$$\left.\begin{array}{l}\lambda_{SW}^U = 66 \\ \lambda_{SW}^L = 9{,}900\end{array}\right\} \quad \lambda_{SW}^L \Big/ \lambda_{SW}^U = 150$$

Observed $\lambda = 11{,}976$

Assumptions

1. Limiting values of π_G, λ_b used, since construction detail is unknown.

Example 2

Data Source: Failure Rate Data (FARADA), June 1967.

Description: Switch is SPST push button run at a cycling rate of 20 cycles per minute; operating in a laboratory environment.

λ is expressed in failures per million hours.

λ_b = (limits are 0.05 and 0.1)

π_{cyc} = 1,200

π_C = 1.0

π_E = 1.0

π_G^U = 0.2

π_G^L = 15.0

$\left.\begin{array}{l} \lambda_{SW}^U = 12 \\ \lambda_{SW}^L = 1{,}800 \end{array}\right\} \lambda_{SW}^L / \lambda_{SW}^U = 150$

Observed λ = 11,448

Assumptions

1. Limiting values of π_G, λ_b used, since construction detail is unknown.

Example 3

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Switch is sensitive SPDT snap action run at a cycling rate of 70 cycles per minute; operating in a laboratory environment.

λ is expressed in failures per million hours.

$\lambda_b = 0.05$

$\pi_{cyc} = 4{,}200$

$\pi_C = 1.75$

$\pi_E = 1.0$

$\pi_G^U = 0.07$

$\pi_G^L = 36.0$

$$\left.\begin{array}{l}\lambda_{SW}^U = 25.7 \\ \lambda_{SW}^L = 13{,}230\end{array}\right\} \lambda_{SW}^L / \lambda_{SW}^U = 514$$

Observed $\lambda = 21{,}243$

Example 4

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Switch is sensitive SPDT snap action run at a cycling rate of 150 cycles per minute; operating in a laboratory environment.

λ is expressed in failures per million hours.

$\lambda_b = 0.05$

$\pi_{cyc} = 9,000$

$\pi_C = 1.75$

$\pi_E = 1.0$

$\pi_G^U = 0.07$

$\pi_G^L = 36.0$

$$\left.\begin{array}{l}\lambda_{SW}^U = 55.1 \\ \\ \lambda_{SW}^L = 28,350\end{array}\right\} \lambda_{SW}^L / \lambda_{SW}^U = 514$$

Observed $\lambda = 70,926$

Example 5

Data Source: Schafer, R. and Yurkowsky, W., Accelerated Test Methods for Mechanical and Electromechanical Parts, Technical Report No. RADC-TR-65-46, July 1965.

Description: Switch is sensitive SPDT snap action run at a cycling rate of 300 cycles per minute; operating in a laboratory environment.

λ is expressed in failures per million hours.

$\lambda_b = 0.05$

$\pi_{cyc} = 18,000$

$\pi_C = 1.75$

$\pi_E = 1.0$

$\pi_G^U = 0.07$

$\pi_G^L = 36.0$

$$\left.\begin{array}{l} \lambda_{SW}^U = 110.3 \\ \\ \lambda_{SW}^L = 56,700 \end{array}\right\} \lambda_{SW}^L / \lambda_{SW}^U = 514$$

Observed $\lambda = 187,652$

Section 7.0 Appendix

Subsection 7.4 CONTRIBUTING SOURCES, FAILURE DISTRIBUTION CONSENSUS

Source numbers refer to the Bibliography, Subsection 7.8.

Bearings

Source No. 22
Opinion: Weibull, $\beta = .93$

Source No. 30
Opinion: Weibull, $1 < \beta < 3$

Source No. 31
Opinion: Weibull

Source No. 29
Opinion: Weibull, $0.54 \leq \beta \leq 3.82$

Source No. 8
Opinion: Weibull, $\beta = 1.17$

Source No. 49
Opinion: Weibull

Source No. 11
Opinion: Weibull

Source No. 1
Opinion: Weibull

Source No. 38
Opinion: Weibull

Source No. 21
Opinion: Weibull

Source No. 26
Opinion: Weibull

Source No. 47
Opinion: Weibull

Gears

Source No. 9
Opinion: exponential

Source No. 8
Opinion: exponential

Gears (Continued)

Source No. 11
Opinion: Weibull, $\beta = 0.8$, $\alpha = 4.8 \times 10^7$

Gyros

Source No. 50
Opinion: mixed Weibull, $\beta_1 = 0.6$, $\beta_2 = 2.4$

Source No. 42
Opinion: mixed Weibull, $\beta_1 = 0.6$, $\beta_2 = 1.7$

Motors

Source No. 22
Opinion: Weibull, $\beta = 0.76$

Source No. 5
Opinion: mixed Weibull, $\beta_1 = 0.6$, $\beta_2 = 1.81$, $\alpha_1 = 11.02$, $\alpha_2 = 330.3$

Source No. 50
Opinion: mixed Weibull, $\beta_1 = 0.65$, $\beta_2 = 2.25$

Source No. 10
Opinion: exponential

Pumps

Source No. 22
Opinion: Weibull, $\beta = 0.99$

Relays

Source No. 19
Opinion: Weibull, $1.5 \leq \beta \leq 3.2$, $1.56 \times 10^8 \leq \alpha \leq 6.7 \times 10^{16}$

Source No. 17
Opinion: Weibull, $\beta = 1.71$, $\alpha = 9.48 \times 10^9$

Source No. 43
Opinion: Weibull, $1.72 \leq \beta \leq 3.8$, $2.03 \times 10^{10} \leq \alpha \leq 8 \times 10^{22}$

Source No. 44
Opinion: Weibull, $\beta = 1.68$, $\alpha = 8.15 \times 10^{19}$

Source No. 33
Opinion: Weibull, $\beta = 0.5$, $\alpha = 448$

Source No. 22
Opinion: Weibull, $0.53 \leq \beta \leq 0.63$

Relays (Continued)

Source No. 10
Opinion: exponential

Source No. 34
Opinion: Weibull, $\beta = 2.0$, $\alpha = 10^{12}$

Source No. 6
Opinion: Weibull, $\beta = 0.66$, $\alpha = 1.54 \times 10^{6}$

Seals

Source No. 22
Opinion: Weibull, $0.8 \leq \beta \leq 1.47$

Source No. 44
Opinion: Weibull, $\beta = 17.75$, $\alpha = 3.5 \times 10^{57}$

Springs

Source No. 22
Opinion: Weibull, $\beta = 1.47$

Switches

Source No. 22
Opinion: Weibull, $0.43 \leq \beta \leq 0.79$

Source No. 43
Opinion: Weibull, $3.228 \leq \beta \leq 7.88$, $2.82 \times 10^{16} \leq \alpha \leq 8.35 \times 10^{42}$

Source No. 44
Opinion: Weibull, $\beta = 4.07$, $\alpha = 5.38 \times 10^{21}$

Source No. 10
Opinion: Weibull, $\beta = 0.7$

Valves

Source No. 22
Opinion: Weibull, $0.81 \leq \beta \leq 0.96$

Section 7.0 Appendix

Subsection 7.5 REGRESSION DATA FOR FAILURE RATE VERSUS STRESS

PART TYPE: FANS

Typical Temperature in Degrees Centigrade	Failure Rate in Failures Per Million Hours
18	.26
25	31.8
50	84.7
54	167
55	72.3
60	250
125	52

PART TYPE: RELAYS

Typical Relative Humidity in Percent	Failure Rate in Failures Per Million Hours
30	50
35	10
40	.79
57.5	.44
60	14.4
85	53
100	109

Typical Temperature in Degrees Centigrade	Failure Rate in Failures Per Million Hours
0	48.3
10	4.16
21	.44
22	37.97
25	5.87
27	14.4
30	.74
40	5.8
45	52.6
50	12.1
55	10.3
60	4.1

PART TYPE: SWITCHES

Percent of Rated Current	Failure Rate in Failures Per Million Hours
.6	331
3	17
10	7
20	297
45	21.8
75	10.1

Typical Relative Humidity in Percent	Failure Rate in Failures Per Million Hours
35	5.15
40	.127
50	12.5
60	6.4
85	40
90	24.4
100	8.1

Typical Temperature in Degrees Centigrade	Failure Rate in Failures Per Million Hours
-7	105
0	6.1
7	92
10	186
25	7.61
27	6.4
30	.13
40	353
45	40
50	40
52.5	13.7
55	5.15
60	1.4
66	288

Section 7.0 Appendix

Subsection 7.6 RESULTS OF SIGNIFICANCE TEST ON APPLICATION FACTORS

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Actuators, Hydraulic	1 Ground 2 Air	364 6,726	.019*	.87
	1 Helicopter 2 Air	44 6,726	.44*	.68
Bearings, Ball	1 Sim Air 2 Air	6 94	.90	.27
	1 Ship 2 Air	20 94	.0012*	.525
	1 Air, Ground 2 Air	130 94	.69*	.74
Connections, Soldered	1 Air 2 Laboratory	430 2,002	.13*	.37
	1 Ground 2 Air	1,246 430	.13*	.86
	1 Ship 2 Air	30 430	.24*	.60
Connections, Welded	1 Lab 2 Air	8 20	.90	.318
	1 Ground 2 Air	10 20	.04*	.360

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Connectors, Circular, Multipin	1 Air 2 Ground	564 108	.95	.78
	1 Air, Ground 2 Air	48 564	.11*	.68
	1 Air 2 Sim. Missile	564 66	.049*	.75
Connectors, Coaxial	1 Lab 2 Air	4 152	.052*	.177
	1 Air 2 Ground	152 1,772	.20*	.80
	1 Air 2 Submarine	152 68	.029*	.71
Connectors, Rectangular	1 Lab 2 Air	6 88	.0068*	.27
Generators, AC	1 Helicopter 2 Air	16 12,026	.42*	.50
Generators, DC	1 Helicopter 2 Air	16 784	.43*	.49
	1 Air 2 Air, Ground	784 184	.57*	.80
Gyros, Free-Directional	1 Air 2 Helicopter	10,212 1,136	.54*	.97
	1 Air Ground 2 Air	50 10,212	.76	.694

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Gyros, Free-Vertical	1 Air 2 Air, Ground	7,078 1,632	.71*	.95
Gyros, Integrating,	1 Lab 2 Air	74 16	.66	.55
	1 Air 2 Ground	16 142	.898	.48
Gyros, Rate	1 Lab 2 Air	36 4,534	.20*	.645
	1 Ground 2 Air	450 4,534	.46*	.89
	1 Air 2 Helicopter	4,534 114	.849	.81
	1 Air 2 Air, Ground	4,534 44	.084	.72
Pumps, Electrically Driven	1 Lab 2 Air	124 1,202	.715*	.82
	1 Air 2 Air, Ground	1,202 12	.128*	.57

*Denotes significance at the F.05 level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Pumps, Engine Driven	1 Air 2 Air, Ground	8,654 26	.277*	.67
Pumps, Fuel or Booster	1 Ground 2 Air	64 8,408	.86	.73
	1 Helicopter 2 Air	66 8,408	.995	.73
Pumps, Hydraulic	1 Ground 2 Air	12 11,030	.002*	.436
	1 Helicopter 2 Air	326 11,030	.485*	.85
	1 Storage 2 Air	16 11,030	.0001*	.49
	1 Air 2 Missile	11,030 6	.0445*	.476
Relays, Armature	1 Lab 2 Air	84 22,378	.256*	.75
	1 Ground 2 Air	234 22,378	.756*	.84

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Relays, Armature (Cont'd)	1 Ship 2 Air	342 22,378	.376*	.87
Relays Contactor	1 Ground 2 Air	16 102	.106*	.48
Relays, Thermal	1 Ground 2 Air	12 4	.065*	.307
	1 Air, Ground 2 Air	4 4	.933	.157
Relays, Time Delay	1 Lab 2 Air	8 48	.094*	.33
	1 Ground 2 Air	52 48	.224*	.62
	1 Air, Ground 2 Air	40 48	.885	.60
	1 Submarine 2 Air	8 48	.0246*	.33
	1 Ship 2 Air	48 48	.346*	.62
Resistors, Variable, Composition	1 Lab 2 Air	6 274	.00645*	.27
	1 Ground 2 Air	894 274	.392*	.87
	1 Sim. Air 2 Air	12 274	.453	.43

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Resistors, Variable, Composition (Cont'd)	1 Air 2 Air, Ground	274 272	.613*	.85
Resistors, Variable, Film	1 Air 2 Air, Ground	14 50	.713	.44
	1 Air 2 Missile	14 12	.0695*	.393
Resistors, Variable, Wirewound	1 Lab 2 Air	34 402	.055*	.85
	1 Ground 2 Air	312 402	.29*	.85
	1 Air 2 Sim. Air	402 102	.175*	.62
	1 Ship 2 Air	8 402	.019*	.34
	1 Air 2 Air, Ground	402 480	.95	.83
	1 Storage 2 Air	10 402	.005*	.39
	1 Air 2 Missile	402 8	.0298*	.508
Seals, Rotary	1 Air 2 Helicopter	1,538 854	.086*	.95

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Seals, Stationary	1 Ground 2 Air	28 6,476	.261*	.60
	1 Air 2 Helicopter	6,476 8	.78	.516
Switches, Pushbutton	1 Lab 2 Air	38 200	.09*	.64
	1 Ground 2 Air	8 200	.0098*	.34
	1 Sim. Air 2 Air	6 200	.545	.27
Switches, Rotary	1 Lab 2 Air	8 464	.105*	.34
	1 Ground 2 Air	100 464	.1025*	.75
	1 Air 2 Air, Ground	464 146	.785	.78
	1 Air 2 Submarine	464 12	.04*	.564
Switches, Snap-Action	1 Ground 2 Air	54 390	.148*	.69
	1 Air 2 Missile	390 6	.061*	.47
	1 Submarine 2 Air	104 390	.0725*	.76

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Switches, Snap-Action (Cont'd)	1 Sim. Air 2 Air	4 390	.42	.177
Switches, Toggle	1 Ground 2 Air	268 400	.0825*	.83
	1 Sim. Air 2 Air	4 400	.641	.177
	1 Air, Ground 2 Air	32 400	.664	.61
Synchros, Control Resolver	1 Ship 2 Air	6 482	.388	.27
	1 Air 2 Helicopter	482 28	.322*	.67
	1 Ground 2 Air	34 482	.183*	.63
Synchros, Control Transformer	1 Submarine 2 Air	52 20	.088*	.564
Synchros, Control Transmitter	1 Sim. Air 2 Air	52 4	.271*	.392
Tanks, Compressed Gas	1 Air 2 Ground	2,728 10	.325*	.546

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Tanks, Fuel Cells	1 Air 2 Helicopter	4,006 144	.98	.82
Tanks, Reservoirs	1 Air 2 Helicopter	2,418 160	.147*	.83
Thermostats	1 Ground 2 Air	74 6,298	.0158*	.74
Transducers, Pressure	1 Air 2 Ground	1,502 26	.985	.67
Transducers, Temperature	1 Air 2 Sim. Air	1,084 6	.332*	.476
	1 Air 2 Ship	1,084 20	.985	.637
Valves, Check	1 Air 2 Ground	4,538 22	.13*	.64
	1 Lab 2 Air	4 4,538	.13*	.18
Valves, Control	1 Air 2 Ground	6,002 28	.08*	.66
Valves, Relief	1 Air 2 Ground	2,802 14	.065*	.60

*Denotes significance at the $F_{.05}$ level.

Part Type	Environments Compared	Degrees of Freedom	F Ratio (λ_1/λ_2)	$F_{.05}$
Valves, Shutoff	1 Air 2 Helicopter	8,446 40	.56*	.72
Valves, Solenoid	1 Air 2 Helicopter	1,006 20	.55*	.64

*Denotes significance at the $F_{.05}$ level.

Subsection 7.7 FAILURE RATES AND CONFIDENCE LIMITS BY ENVIRONMENT

ENVIRONMENT: AIR

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Actuators, Hydraulic	378.58	368.02 - 389.50
Actuators, Pneumatic	72.82	59.06 - 90.45
Bearings, Ball	6.44	5.09 - 8.24
Bearings, Rod End	7.96	7.12 - 8.89
Bearings, Roller	.86	.54 - 1.43
Capacitors, Variable, Air		0 - 23.26
Capacitors, Variable, Ceramic		0 - 41.12
Capacitors, Variable, Glass	10.75	3.82 - 51.01
Connections, Soldered	.035	.031 - .039
Connections, Welded	.052	.031 - .091
Connections, Wire Wrap		0 - .023
Connectors, Circular, Multipin	.98	.89 - 1.09
Connectors, Coaxial	2.70	2.26 - 3.30
Connectors, Rectangular	22.20	17.39 - 28.62
Generators, AC	1,120	442.41 - 522.43
Gyros, Free-Directional	1,430	1,398 - 1,464
Gyros, Free-Vertical	1,298	1,262 - 1,334
Gyros, Integrating	368.42	209.52 - 692.00
Gyros, Rate	351.23	339.33 - 363.61
Pumps, Electrically Driven	321.12	300.23 - 343.37
Pumps, Engine Driven	664.93	648.54 - 681.80
Pumps, Fuel or Booster	170.43	166.18 - 174.83
Pumps, Hydraulic	808.87	791.19 - 827.03
Pumps, Vacuum	729.13	770.64 - 814.92
Relays, Armature	16.61	16.35 - 16.87
Relays, Contactor	9.50	7.57 - 12.03
Relays, Rotary		0 - 146.66
Relays, Thermal	200	71.07 - 948.77
Relays, Time Delay	27.17	19.15 - 37.71
Resistors, Variable, Composition	18.61	16.15 - 21.40
Resistors, Variable, Film	5.34	2.92 - 10.54
Resistors, Variable, Wirewound	9.94	8.86 - 11.18
Seals, Aerodynamic	27.35	20.37 - 37.30
Seals, Rotary	27.55	25.97 - 29.25
Seals, Stationary	67.58	65.66 - 69.56
Switches, Limit	68.77	65.19 - 72.53
Switches, Pushbutton	21.39	18.23 - 25.35
Switches, Rotary	17.04	15.32 - 19.01

Environment: AIR (Cont'd)

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Switches, Snap-Action	15.33	13.62 - 17.24
Switches, Toggle	6.91	6.16 - 7.78
Synchros, Control Resolver	139.72	125.78 - 155.49
Synchros, Control Transformer	2.05	1.24 - 3.59
Synchros, Control Transmitter	.65	.23 - 3.08
Tanks, Compressed Gas	164.75	157.60 - 172.29
Tanks, Fuel Cells	160.78	155.01 - 166.83
Tanks, Reservoir	74.30	70.88 - 77.92
Thermostats	258.21	250.77 - 265.91
Transducers, Pressure	848.57	799.35 - 901.34
Transducers, Temperature	93.32	86.99 - 100.20
Valves, Check	40	38.7 - 41.4
Valves, Control	138	134 - 142
Valves, Relief	46	44.0 - 48.1
Valves, Shutoff	88.7	86.5 - 91.0
Valves, Solenoid	82	76.2 - 88.3

ENVIRONMENT: <u>GROUND</u>

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Actuators, Hydraulic	7.15	6.34 - 8.09
Bearings, Ball		0 - 4.21
Bearings, Rod End		0 - 234.62
Capacitors, Variable, Air	66.67	32.84 - 152.56
Capacitors, Variable, Ceramic	.76	.35 - 1.96
Capacitors, Variable, Glass		0 - 93.15
Connections, Crimped	.0073	.0047 - .0119
Connections, Soldered	.0044	.0041 - .0047
Connections, Welded	.0022	.0011 - .0049
Connections, Wire Wrap	.00000375	.00000151 - .00001166
Connectors, Circular Multipin	1.03	.83 - 1.30
Connectors, Coaxial	13.31	12.60 - 14.07
Connectors, Rectangular		0 - .016
Gyros, Integrating	410.26	338.36 - 500.56
Gyros, Rate	163.15	146.33 - 182.26
Pumps, Fuel or Booster	146.71	110.25 - 198.00
Pumps, Hydraulic	1.68	.088 - 3.52
Pumps, Vacuum		0 - 1,096
Relays, Armature	12.54	10.78 - 14.63
Relays, Contactor	1.01	.58 - 1.90
Relays, Crystal Can	21.28	7.56 - 100.93
Relays, Latching		0 - 34.39
Relays, Reed	3.93	1.79 - 10.15
Relays, Solenoid		0 - 4,428
Relays, Thermal	13.07	6.83 - 22.47
Relays, Time Delay	6.08	4.42 - 8.48
Resistors, Variable, Composition	7.3	6.76 - 7.90
Resistors, Variable, Wirewound	2.88	2.52 - 3.29
Seals, Stationary	17.73	7.61 - 32.93
Switches, Pushbutton	.21	.095 - .54
Switches, Rotary	1.75	1.39 - 2.22
Switches, Snap-Action	2.27	1.66 - 3.14
Switches, Toggle	.57	.50 - .67
Synchros, Control Resolver	25.57	17.31 - 38.83
Tanks, Compressed Gas	506.33	249.39 - 1,158.67
Thermostats	4.08	3.13 - 5.39
Transducers, Pressure	860	511 - 1,391
Valves, Check	310	191 - 526
Valves, Control	1,740	1,133 - 2,766
Valves, Relief	714	391 - 1,404

ENVIRONMENT: LABORATORY

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Capacitors, Variable, Ceramic	.76	.35 - 1.96
Connections, Crimped		0 - 95.95
Connections, Soldered	.270	.257 - .285
Connections, Welded	.047	.035 - .064
Connections, Wire Wrap	.251	.205 - .309
Connectors, Circular, Multipin		0 - .75
Connectors, Coaxial	.14	.05 - .66
Connectors, Rectangular	.15	.061 - .473
Gyros, Integrating	243.41	186.57 - 321.44
Gyros, Rate	69.75	47.73 - 104.60
Pumps, Electrically Driven	230.04	187.20 - 284.70
Relays, Armature	4.26	3.32 - 5.52
Relays, Crystal Can	1.40	.97 - 2.07
Relays, Latching	.04	.01 - .18
Relays, Time Delay	2.54	1.16 - 6.56
Resistors, Variable, Composition	.12	.05 - .37
Resistors, Variable, Film		0 - 143.9
Resistors, Variable, Wirewound	.55	.37 - .83
Switches, Pushbutton	1.91	1.32 - 2.84
Switches, Rotary	1.79	.82 - 4.63
Switches, Snap-Action		0 - 1.81
Switches, Toggle		0 - 1.82
Thermostats		0 - 22.06
Valves, Check	5.00	1.78 - 23.70

ENVIRONMENT: HELICOPTER

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Actuators, Hydraulic	168.28	119.34 - 242.32
Generators, AC	466.67	265.39 - 876.54
Generators, DC	842.59	711.21 - 1,003
Gyros, Free-Directional	2,650	2,474 - 2,850
Gyros, Rate	413.96	333.93 - 517.15
Pumps, Fuel or Booster	169.29	127.77 - 227.38
Pumps, Hydraulic	391.98	344.99 - 446.55
Seals, Rotary	320.39	296.26 - 347.42
Seals, Stationary	86.71	9.76 - 268.03
Synchros, Control Resolver	433.33	282.13 - 68..95
Tanks, Fuel Cells	163.82	135.29 - 199.59
Tanks, Reservoir	634.33	528.96 - 764.89
Valves, Shutoff	158	110 232
Valves, Solenoid	150	90 - 261

ENVIRONMENT: SHIP

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Bearings, Ball	.008	.005 - .015
Connections, Soldered	.0085	.0056 - .0133
Relays, Armature	6.25	5.51 - 7.09
Resistors, Variable, Wirewound	.19	.09 - .49
Synchros, Control Resolver	54.13	22.13 - 170.39
Transducers, Temperature	94.70	57.09 - 165.25

ENVIRONMENT: STORAGE

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)	
Capacitors, Variable, Air		0	8.22
Capacitors, Variable, Glass		0	.165
Generators, AC		0	.50
Pumps, Hydraulic	.08	.04	.15
Relays, Armature		0	.096
Relays, Crystal Can		0	.053
Relays, Rotary		0	14.04
Relays, Solenoid		0	6.22
Relays, Thermal		0	5.03
Resistors, Variable, Composition		0	17.01
Resistors, Variable, Wirewound	.05	.02	.11
Switches, Pushbutton		0	2.37
Switches, Rotary		0	56.16
Switches, Snap-Action		0	6.22

ENVIRONMENT: AIR, GROUND

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Bearings, Ball	4.37	3.58 - 5.39
Connectors, Circular, Multipin	.11	.08 - .16
Generators, DC	843	711 - 1,003
Gyros, Free-Directional	1,090	791 - 1,534
Gyros, Free-Vertical	1,836	1,733 - 1,945
Gyros, Rate	4,200	2,979 - 6,048
Pumps, Electrically Driven	2,500	1,307 - 5,257
Pumps, Engine Driven	2,400	1,538 - 3,881
Relays, Armature	24.25	19.24 - 30.85
Relays, Latching	4.09	1.45 - 19.39
Relays, Thermal		0 - 66.43
Relays, Time Delay		0 - 143.9
Resistors, Variable, Composition	30.36	26.37 - 34.97
Resistors, Variable, Film	7.48	5.41 - 10.51
Resistors, Variable, Wirewound	10.45	9.40 - 11.63
Switches, Pushbutton	11.66	4.77 - 36.71
Switches, Rotary	21.72	17.96 - 26.42
Switches, Toggle	4.58	3.07 - 7.06
Thermostats	5.22	3.61 - 7.74

ENVIRONMENT: SIMULATED AIR

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Bearings, Ball	5.82	2.38 - 18.33
Capacitors, Variable, Air	8.17	4.02 - 18.70
Capacitors, Variable, Ceramic		0 - 1.93
Capacitors, Variable, Glass		0 - 12.86
Connectors, Circular, Multipin		0 - 14.13
Connectors, Coaxial		0 - 5.88
Connectors, Rectangular		0 - 1.82
Relays, Armature	24.25	19.24 - 30.85
Relays, Latching	4.09	1.45 - 19.39
Relays, Thermal		0 - 66.43
Relays, Time Delay		0 - 143.9
Resistors, Variable, Composition	8.42	4.40 - 17.70
Resistors, Variable, Wirewound	56.80	45.27 - 71.89
Switches, Pushbutton	11.66	4.77 - 36.71
Switches, Snap-Action	6.43	2.28 - 30.50
Switches, Toggle	4.43	1.57 - 21.00
Thermostats		0 - 48.22
Transducers, Temperature	281.69	115.17 - 886.73

ENVIRONMENT: SUBMARINE

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Capacitors, Variable, Ceramic		0 - 44.68
Connectors, Coaxial	92.93	70.43 - 124.26
Relays, Time Delay	.67	.31 - 1.74
Switches, Rotary	428.45	223.91 - 900.86
Synchros, Control Resolver	.58	.41 - .85
Synchros, Control Transformer	.18	.13 - .25

ENVIRONMENT: MISSILE

Part Type	Failure Rate (failures per million hours)	90% Confidence Limits (failures per million hours)
Pumps, Hydraulic	18,182	7,434 - 57,235
Resistors, Variable, Film	77	40 - 162
Resistors, Variable, Wirewound	333	152 - 862
Switches, Snap-Action	250	102 - 787

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Section 7.0 Appendix

Subsection 7.9 EXPLANATION OF NEDCO II DATA FORMAT

The computer printout of nonelectronic data is presented in three sections: Section I - Failure Rate Data, Section II - Stress Level Data/Part Number, and Section III - Failure Mode Distributions.

Format of Section I - FAILURE RATE DATA

PART CLASSIFICATION: Parts are classified by generic type, utilizing the first five digits of the IDEP code for part classification. In the NEDCO format, the first three digits of the IDEP code appear with the part type at the top of the page. The fourth and fifth digits of the IDEP code appear with the IDEP part descriptors and are intended as subheadings on each page. Consistent with the IDEP definition, "N.O.C." means "Not Otherwise Classified," in part class or subheading.

PART DESCRIPTION: Additional part descriptive information is presented in this field. The specific part name is listed here when the IDEP classification only groups several similar part types.

FUNCTIONAL APPLICATION: This field describes the subsystem or application in which the part is used. Also, certain operating conditions may appear in parentheses in this field. When the same letter used as a suffix on failure rate, upper 90% confidence limit, and part-hours may have more than one meaning (e.g., M = MISSIONS or M = MILES), its meaning for that line item of data is explained in this field.

ENVIRONMENT: The operating environment is given by the following abbreviations:

LAB = LABORATORY
GRD = GROUND
GRD FXD = GROUND, FIXED
GRD MOB = GROUND, MOBILE
GRD PORT = GROUND, PORTABLE
SHP = SHIPBOARD
SUB = SUBMARINE
SAT = SATELLITE
AIR = AIRCRAFT
AIR CB = AIRCRAFT, CARRIER BASED
AIR LB = AIRCRAFT, LAND BASED
MSL = MISSILE
GEN = GENERAL
LIFE, LAB = LIFE TEST, LABORATORY
LIFE, ACC = LIFE TEST, ACCELERATED
ACCEPT TEST = ACCEPTANCE TEST
STOR = STORAGE
AIR GRD = AIR, GROUND
AIR SHP GRD = AIR, SHIP, GROUND
HELI = HELICOPTER
QUAL TEST = QUALIFICATION AND EVALUATION TEST

SIM GRD = SIMULATED GROUND
SIM SHP = SIMULATED SHIPBOARD
SIM SUB = SIMULATED SUBMARINE
SIM SAT = SIMULATED SATELLITE
SIM MSL = SIMULATED MISSILE
SIM HELI = SIMULATED HELICOPTER
SIM AIR = SIMULATED AIRCRAFT
GRD SHP = GROUND, SHIP
RR = RAILROAD
SIM GRD AIR = SIMULATED GROUND, AIR

FAILURE RATE: Failures per million operating hours are given unless the failure rate is suffixed by a letter. The letter indicates that the failure rate is expressed in failures per million units explained either in the FUNCTIONAL APPLICATION field or as follows:

A = Actuations
C = Cycles
R = Rounds
P = Premature removals per million hours

An asterisk (*) indicates 0 failures.

UPPER 90% CONFIDENCE LIMIT: The upper one-sided 90% confidence limit is given in the units of the failure rate. Letters in suffix relate to units as in the FAILURE RATE field.

PART POPULATION: Total number of parts under observation are given in this field.

PART-HOURS: This field indicates total test time in millions of part-hours unless there is a letter in suffix. The letter is of the same code as the FAILURE RATE field.

YEAR OF REPORT: This date is the one appearing with the originator's data contribution and may represent either the date the data was generated or the date it was published.

DATA SOURCE: This field is a coded indication of the source of the data (see NEDCO II Source List), and is intended for RADC use only.

CROSS INDEX REFERENCE NUMBER: This number relates the failure rate data in Section I to the stress and failure mode information in Sections II and III. The suffix "A" on a number means that there exists supplemental information for the entry in Section II.

Format of Section II - STRESS LEVEL DATA/PART NUMBER

CROSS INDEX REFERENCE NUMBERS: This number relates to the failure rate data in Section I.

MILITARY STANDARD PART NUMBER/FEDERAL STOCK NUMBER: The number provided may be a Military Standard part number or a federal stock number.

PERCENT OF RATED VOLTAGE: The number indicated is the percent of the vendor-rated voltage at which the part was operated.

PERCENT OF RATED CURRENT: The number indicated is the percent of the vendor-rated current at which the part was operated.

PERCENT OF RATED POWER: The number indicated is the percent of the vendor-rated power at which the part was operated.

PERCENT OF RATED FREQUENCY: The number indicated is the percent of the vendor-rated frequency at which the part was operated.

PERCENT OF RATED PRESSURE: The number indicated is the percent of the vendor-rated pressure at which the part was operated.

TYPICAL TEMPERATURE: The number indicated is the ambient temperature of the part in degrees Centigrade which was experienced during operation.

HIGH TEMPERATURE: The number indicated is the greatest ambient temperature of the part in degrees Centigrade which was experienced during operation.

LOW TEMPERATURE: The number indicated is the lowest ambient temperature of the part in degrees Centigrade which was experienced during operation.

FREQUENCY OF SINUSOIDAL VIBRATION: The numbers indicated are an individual value or range of values for the frequency of sinusoidal vibration experienced by the part during operation. Values are presented in terms of cycles per second. The abbreviation K or M in this column indicates respectively kilocycles or megacycles.

INTENSITY OF SINUSOIDAL VIBRATION: The numbers indicated are an individual value or range of values for the intensity of sinusoidal vibration experienced by the part during operation. Values are presented in units of g (root-mean-square value).

INTENSITY OF RANDOM VIBRATION: The number indicated is the intensity of random vibration experienced by the part during operation. Values are presented in terms of the unit g^2 per cycle per second.

ACOUSTICAL VIBRATION: The number indicated is the intensity of acoustical vibration experienced by the part during operation. Values are presented in terms of decibels.

MAXIMUM INTENSITY OF SHOCK: The number indicated is the maximum intensity of shock experienced by the part during operation. Values are presented in units of g.

DURATION OF SHOCK: The number indicated is the average duration of individual shock blows experienced by the part during operation. Values are presented in terms of milliseconds.

SHOCK BLOWS PER HOUR: The number indicated is the average number of shock blows per hour experienced during operation.

TYPICAL PRESSURE: The number indicated is the typical barometric pressure experienced by the part during operation. Values are presented in terms of pounds per square inch absolute.

PRESSURE RANGE: The numbers indicated are the range of barometric pressures experienced by the part during operation. Values are presented in terms of pounds per square inch absolute.

TYPICAL RELATIVE HUMIDITY: The number indicated is the typical relative humidity in percent experienced by the part during operation.

RANGE OF RELATIVE HUMIDITY: The numbers indicated are the range of relative humidity in percent experienced by the part during operation.

Format of Section III - FAILURE MODE DISTRIBUTIONS

CROSS INDEX REFERENCE NUMBER: This number relates to the failure rate data in Section I. A missing cross index reference number indicates that failure rate information is unknown for that line entry.

FAILURE MODES BY PERCENT OF TOTAL FAILURES: The percent of the total number of failures attributed to a particular failure mode is given under a numerical heading in parentheses. The heading number corresponds to a numbered list of possible failure modes given at the beginning of the page(s) for each separate part type.

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13. ABSTRACT

This study addressed itself to the location, collection, classification, organization and analysis of nonelectronic part reliability information into a form from which it can be integrated into a Nonelectronic Reliability Handbook.

The collection phase resulted in 38,761 line entries of failure data on approximately 600 different nonelectronic part types. These data, organized in log groups are presented in the appendix of this report.

The Data Analysis took several forms. Failure information on the same and similar part types was combined to yield overall failure rates for each of several environmental applications. Conversion factors were calculated to reflect the effect of varying severity of environments on part life. Failure rate versus stress relationships were sought but the data collected were not complete enough to yield useful relationships. Most of the failure information collected contained total part operating time and the number of observed failures. With this amount of information the only alternative was to perform the above mentioned analysis tasks as though the hazard rate was constant with time. Several reports were collected which gave good evidence that in truth many types of nonelectronic parts display failure times according to the Weibull distribution with increasing hazard rates with time. Therefore, the failure rates and confidence limits computed based on the assumption of exponentially distributed failure times (where the true failure times are distributed according to some other failure function) should be used in the proper perspective and with care. While the use of the assumption of constant failure rate does yield

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Failure Analysis						
Components						

Abstract Continued:

a less precise estimate of the true hazard rate it is the only alternative as long as the failure data are recorded for these part types without the inclusion of individual part failure time.

Since it was established that the statistical methods applicable to the reliability of nonelectronic parts must differ from those used traditionally for electronic parts, prediction models applicable to nonelectronic parts were sought. Three models showing promise are investigated in the Data Analysis Section and are compared with field data collected during the study. In each case more verification is required but the models included appear to be useful contributions to the field of nonelectronic part reliability.

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